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Monterey, California

THESIS

HIGH ENERGY ELECTRON RADIATION DEGRADATION
OF GALLIUM ARSENIDE SOLAR CELLS

by

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High Energy Electron Radiation Degradation of Gallium Arsenide Solar Cells

by

Don William Gold
Lieutenant, United States Navy
B.S., United States Naval Academy, 1978

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

A need existed to perform high energy electron irradiation experiments on gallium arsenide solar cells. To support this research, an automated solar cell test facility was constructed, gallium arsenide solar cells were obtained, and the Naval Postgraduate School LINAC facility was utilized to irradiate the cells to selected fluence levels at 20 MEV energies. Equivalent damage coefficients were calculated, and it was found that the average maximum power output decreased by 50 % following a cumulative irradiation by electrons to a total fluence of 1×10^{15} e/cm^2.

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The author wishes to thank Distinguished Professor A. E. Fuhs for his guidance in the preparation of this thesis, and Mr. Don Snyder for his time spent operating the LINAC. The author also thanks his brother Bill for providing technical advice. Additionally, the author wishes to thank his wife and daughter for their support and humor and making the entire experience enjoyable.

I. INTRODUCTION

Extensive research has been performed on gallium arsenide (AlGaAs-GaAs) solar cells concerning their superior hardness with respect to electron radiation degradation when compared with silicon solar cells. Because of known extra-terrestrial electron energies, the majority of published irradiation studies have been performed using 1 million electron volts (MEV), or lower, electron energies. Further, much of the research has utilized non-production type GaAs solar cells. Thus, a need existed to perform electron irradiation experiments on production run cells at electron energies greater than 1 MEV.

To support this research, the capability to measure accurately the electrical characteristics of illuminated solar cells was required. Additionally a source of high energy electrons with which to perform irradiations was needed.

A facility that provides electrons in the 20 to 100 MEV energy spectrum is available for use through the Naval Postgraduate School´s Department of Physics. Thus, the task remained to construct an operating solar cell laboratory to assess cell parameters before and after electron irradiations.

The majority of the components with which to equip such a laboratory had previously been purchased; See Mabie [Ref. 1: pp. 35-48]. This equipment included an IBM PC/XT computer, a Kratos SS 2500 Solar Simulator, an HP 7475A graphics plotter, an IBM 4 channel, 12 bit analog-to-digital converter card, and a National Instruments general purpose interface bus (GPIB) card. To complete the laboratory, a decision was made to purchase an HP 6825A/59501B bipolar power supply combination to function as an active load for the solar cells and an HP 3478A GPIB-capable digital multimeter to measure cell current.

A report of the integration of the above components into a cohesive solar cell testing system, and the subsequent purchase, irradiation, and testing of AlGaAs-GaAs solar cells is the subject of this thesis.

Chapter II discusses the system structure and computer interface.

Chapter III provides narrative concerning the software written to support the automated solar cell testing routine.

The method used to select the gallium arsenide cells for the irradiation experiments and the subsequent test program is covered in Chapters IV and V, respectively.

A discussion of the test results, including calculated equivalent damage coefficients and an analysis of the possible errors in the data is provided in Chapter VI.

Conclusions based on the results of the irradiated cell tests, as well as a recommendation for further solar cell testing, is provided in Chapter VII.

II. SOLAR CELL LABORATORY SYSTEM DESIGN

A. SYSTEM STRUCTURE

The solar cell testing system consists of five main components. The first is the IBM PC/XT computer. This component, with its associated software, controls the data acquisition and power supply components. Included within the PC/XT component is the Hewlett Packard 7475A plotter. A more complete description of the IBM PC/XT computer and the HP plotter may be found in Mabie [Ref. 1: pp. 38-39].

The Data Acquisition and Control element is the next major component of the system. This component consists of a 12 bit, 4 channel analog-to-digital converter (DAC adapter), internal to the IBM PC/XT, and a Hewlett Packard model 3478A Digital Multimeter, operating over an IEEE-488 General Purpose Interface Bus (GPIB). Both devices are controlled by the PC/XT and provide voltage and current measurements of the cell under test. Technical specifications for these devices may be found in Appendix A.

The third component of the test system is the combination of the Hewlett Packard model 59501B Power Supply Programmer and the model 6825A Bipolar Power Supply. The power supply programmer operates over the IEEE-488 interface bus and allows remote programming of the 6825A (operating in

the current sink mode). Technical specifications for these two components are found in Appendix A.

The fourth component of the test system is the Kratos Model SS 2500 Solar Simulator. A complete description of the Kratos light source may be found in Appendix A.

A determination was made of the spectral output of the Kratos light source to verify close approximation to the solar constant both spectrally and in magnitude. This was accomplished by taking short circuit current readings from six different gallium arsenide solar cells illuminated by the sun at local noon and illuminated by the Kratos source. Before the readings were taken, one of six bandpass filters was placed in front of the cell to provide a wavelength dependent output. Thus, a relative spectral output of the Kratos source was determined. This procedure may be algebraically verified since the cell output current, i, is equal to the cell area, A, times the integral over the total input wavelength of the products of the cell's spectral response, R_λ, the filter transmission response, T_λ, and the input spectral intensity, I_λ from the simulator $\left(I_\lambda^{sim}\right)$ or from the sun $\left(I_\lambda^{sun}\right)$. This may be written as

$$i = A \int_{\lambda_1}^{\lambda_2} R_\lambda \; T_\lambda \; I_\lambda \; d\lambda \qquad (1)$$

For the relative output current then,

$$\frac{i_\lambda^{sim}}{i_\lambda^{sun}} = \frac{A \int_{\lambda_1}^{\lambda_2} R_\lambda \; T_\lambda \; I_\lambda^{sim} \, d\lambda}{A \int_{\lambda_1}^{\lambda_2} R_\lambda \; T_\lambda \; I_\lambda^{sun} \, d\lambda} \tag{2}$$

The limits of integration are defined by the bandpass of the optical filters ($\Delta\lambda$). Since R_λ and I_λ do not vary significantly over the narrow band of the filters, ($2\Delta\lambda$), equation (2) may be rewritten as

$$\frac{i_\lambda^{sim}}{i_\lambda^{sun}} = \frac{A \; R_\lambda \;\; I_\lambda^{sim} \int_{\lambda-\Delta\lambda}^{\lambda+\Delta\lambda} T_\lambda \;\; d\lambda}{A \; R_\lambda \;\; I_\lambda^{sun} \int_{\lambda-\Delta\lambda}^{\lambda+\Delta\lambda} T_\lambda \;\; d\lambda} \tag{3}$$

Equation(3) may be simplified by cancelling like terms to arrive at a final result

$$\frac{i_\lambda^{sim}}{i_\lambda^{sun}} = \frac{I_\lambda^{sim}}{I_\lambda^{sun}} \tag{4}$$

For each filter bandpass 12 short circuit current values were averaged for solar illumination and 25 short circuit current values were averaged for simulator illumination. Standard deviations for each illumination method and bandpass were then computed. The values for i^{sim} and i^{sun} were plotted and may be seen in Figure (1) as a function of wavelength. Error bars are included to indicate a 95 % confidence limit. The bandpass of each filter was nominally 10 nanometers and this is also indicated in the figure. The tabulated data may be seen in Table 2-1.

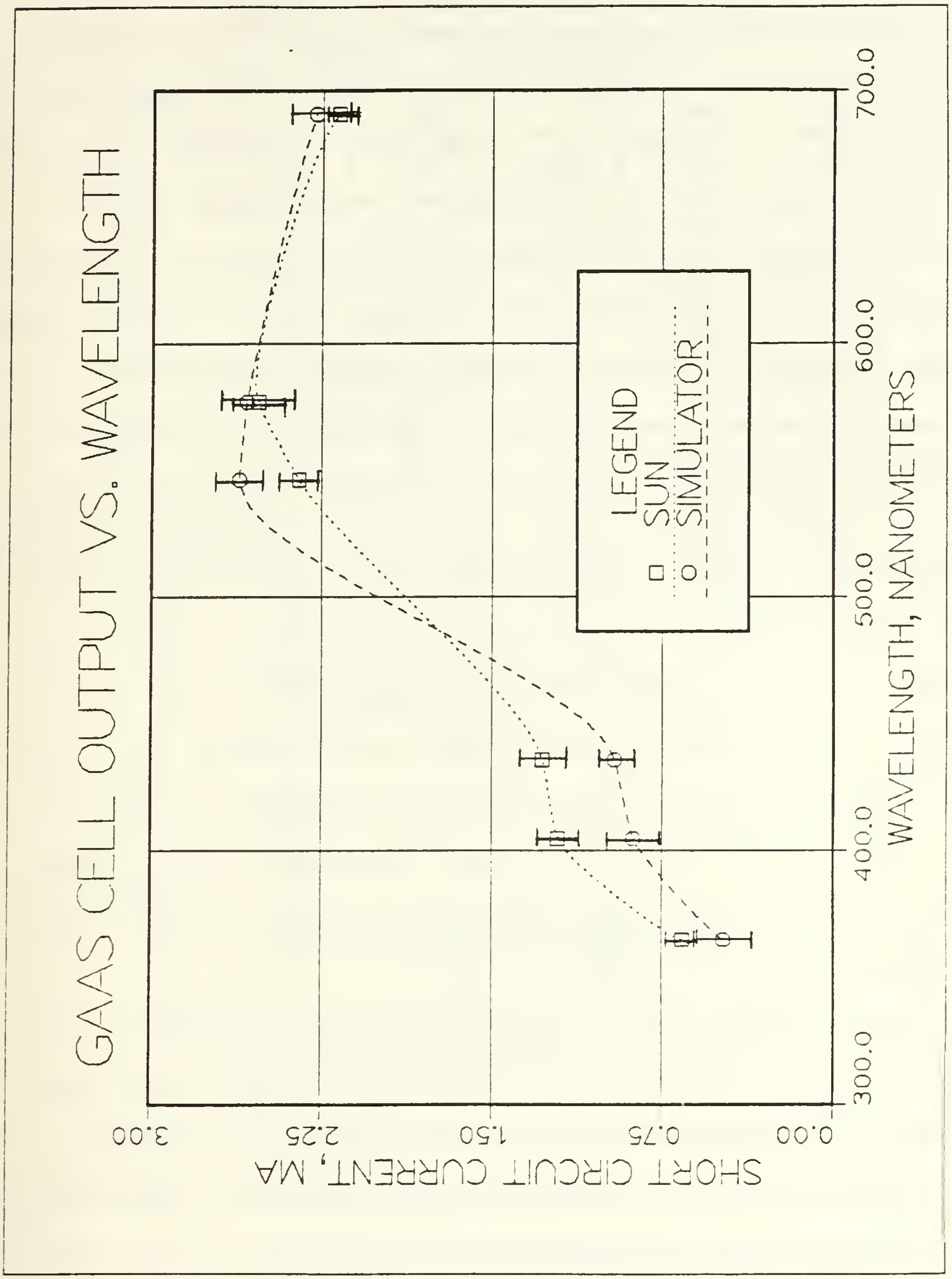


Figure 1. Gallium Arsenide Solar Cell Output (i^{sim} and i^{sun}) as a Function of Wavelength.

TABLE 2-1

KRATOS SPECTRAL OUTPUT RESULTS

	SUN		SIM		
λ nM	i mA	σ	i mA	σ	$\frac{i_{sim}}{i_{sun}}$
365.0	.661	.026	.480	.060	.7262
404.7	1.21	.047	.879	.067	.7264
435.8	1.28	.061	.963	.045	.7523
546.1	2.35	.047	2.61	.053	1.11
577.0	2.53	.059	2.58	.097	1.02
690.7	2.18	.036	2.28	.062	1.04

The fifth component of the system is the combination of the temperature control water circulator and the cell test block. Both of these devices are described in detail in Mabie [Ref. 1: p. 37]. The test block utilizes a four point electrical connection to the solar cell. That is, two separate pairs of wires are used to measure cell voltage and current. This connection effectively eliminates the problem of correcting for lead and contact resistance in the cell measurements [Ref. 2: p. 389].

The temperature control maintains a constant test block temperature to within +/- 0.5 degrees Celsius, over the range -20 to +70 degrees Celsius. The single deficiency to the circulator is that it requires approximately 1 hour to stabilize at the desired operating temperature.

B. SYSTEM OPERATION

The theory behind testing an active device such as a solar cell is discussed extensively in Rauschenbach [Ref. 2: pp. 376-406]. Basically, by varying the resistance of a load from zero to infinity, the solar cell load is changed from a short circuit to an open circuit. Thus, short circuit current (I_{sc}) and open circuit voltage (V_{oc}) may be determined by appropriate measurements. These values are indicated on the current vs. voltage (I-V) curve shown in Figure (2). As the load is varied, the curve that results quantitatively describes the characteristics of the

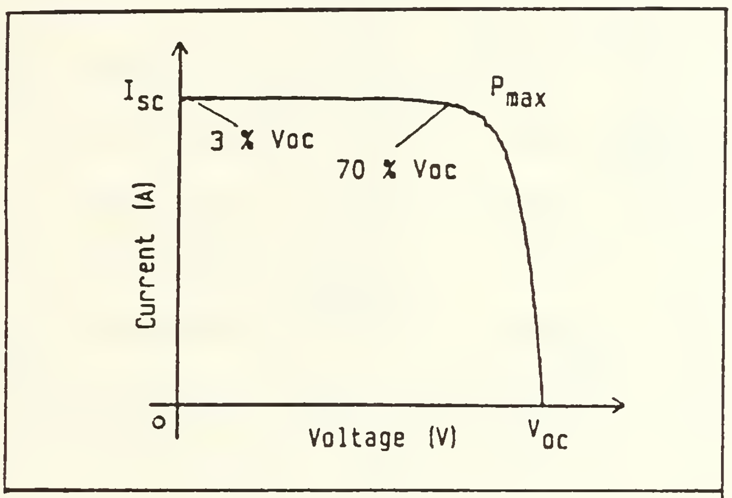


Figure 2. Typical Characteristic Curve for an Illuminated Solar Cell.

cell. Instead of using a passive load however, an active load may also be used. The advantage is that the load resistance may actually be varied between zero and infinity, which is not possible with a practical potentiometer. The

active load used in this system is the Hewlett Packard 6825A bipolar power supply. The source and sink characteristics for this device are included in the technical specifications in Appendix A.

For this application the power supply is operated in the second quadrant, functioning as a current sink.

The block diagram for the electrical components is shown in Figure (3). The test module contains switches for selection of either N/P or P/N solar cells (allowing for reversal of cell polarity), calibration or run functions, and test or setup functions. The wiring diagram for the test module is shown in Figure(4).

To perform a test, the voltage of the power supply is programmed to a value equal to the measured open circuit voltage of the cell, at which time the test/setup switch is placed in the test position thereby completing the test circuit. The power supply output is stepped down while sinking cell current until the voltage measured at the solar cell is less than or equal to zero. During this stepping process, current and voltage readings are taken so as to construct an I-V curve. Once the I-V data are obtained the maximum power, voltage, and current points are determined. The maximum power point is illustrated on the I-V curve of Figure (2).

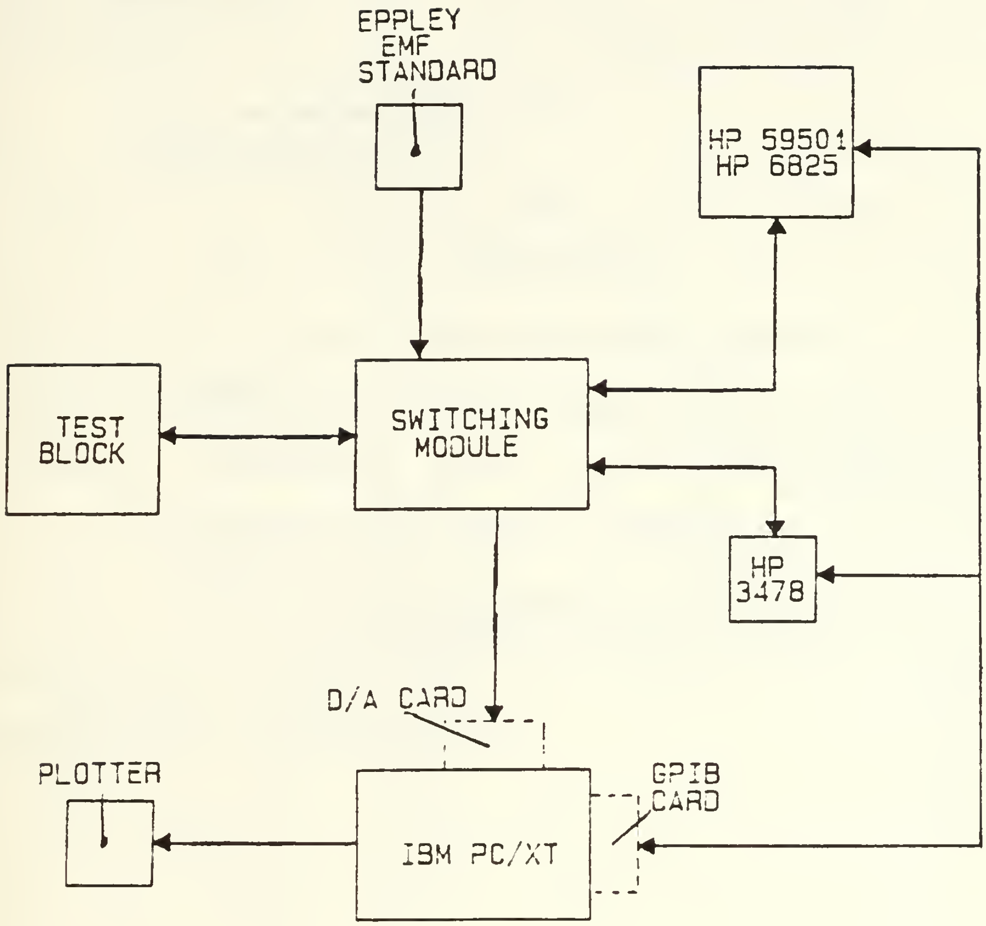


Figure 3. Block Diagram of the Electrical Components for the Solar Cell Testing System.

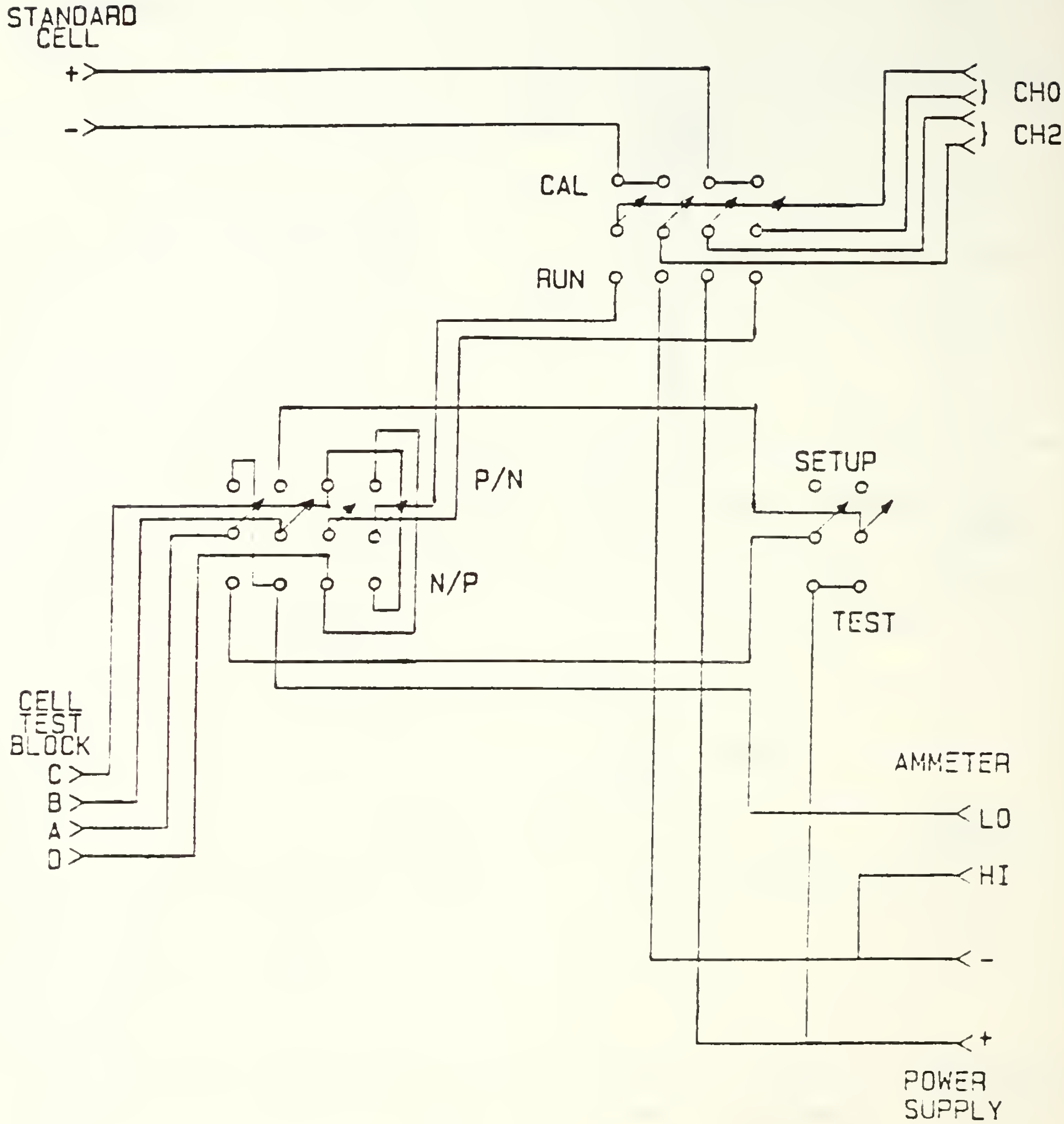


Figure 4. Wiring Diagram for the Switching Module in the Solar Cell Testing System.

Detailed operational and calibration procedures for the system are found in Appendix B.

C. COMPUTER INTEGRATION

The inclusion of the computer into the testing system allows for repeatability, accuracy, and speed in data acquisition and reduction. In addition to the standard graphics, serial, and parallel I/O cards, the IBM PC/XT is equipped with a National Instruments General Purpose Interface Bus (GPIB) card. This device allows communication to and from the power supply programmer and the digital multimeter (acting as the data acquisition component for cell current). The other unique card in the computer is the IBM 4 channel analog-to-digital converter. This device allows data acquisition of the cell and power supply output voltages. The program used to control the computer is discussed fully in Chapter III.

III. SOFTWARE DESIGN

A. INITIAL PLANNING

The prerequisites for the test program were that it must be fast yet flexible enough so that a novice at solar cell testing could obtain accurate and repeatable results. The program was required to contain the separate drivers for the General Purpose Interface Bus (GPIB) and the Analog-to-Digital (A/D) cards which had previously been purchased. The novice operability requirement dictated a menu-driven program to enable easy access to the various test features as desired. These features were as follows: calibration, test, and output. The program developed into nine subroutines: two for input, one for cell testing, five for output, and one to exit to the disk operating system (DOS). Each of these nine subroutines is menu selected and returns to the menu upon completion with the exception of the exit routine. The final flow chart to support the cell test program is included as Appendix C.

B. SOLAR CELL TEST ROUTINE

Based on the above prerequisites and flowchart, the program was developed in three phases: input routines, data acquisition routine, and output routines. The line numbers in the following paragraphs refer to the program in Appendix D.

1. Input Routines

The input routines comprise two of the nine possible menu selections. The first is the data acquisition calibration routine. This selection is required prior to running a solar cell parameter test. The routine utilizes an Eppley low-temperature-coefficient standard of EMF as a known voltage source and then calculates the two offset values for channels 0 and 2 of the DAC adapter based on this known voltage. As was discussed in the introduction, the 12 bit A/D is set for a +/- 5 volt input. Therefore the voltage measured for any given input is equal to

$$V_{meas} = \text{digital word} \times \text{range} / 2^{12} - V_{offset} \quad (5)$$

The digital word is a value dependent on the input voltage present at the A/D input when it is programmed to sample and varies from 0 to 4096. Range is a selectable feature and is either 10 or 20. V_{offset} is a value dependent on the selected A/D range. For the +/- 5 volt range used here, V_{offset} should be 5 volts. It was found that the offset value used with the DAC adapter calculations was not equal to 5 volts and actually varies over a period of time. This variability dictated a calibration routine resident in the test program and is found within lines 2620 - 2980. Use of this routine will be discussed in Appendix C.

The second input routine is found within lines 6320 to 6620. The floppy disk read routine allows data previously recorded on a 5 inch floppy disk to be read into the program and thus to be accessible to the output and graphing routines. This feature allows pre-irradiation and post-irradiation I-V curves to be plotted on the same set of axes.

2. Data Acquisition Routine

The data acquisition routine involves the cell test subroutine and begins at line number 3000. Operator instructions are displayed to place the cell in the test fixture as well as to input the cell ID and size. Since the gallium arsenide solar cells are sensitive to current surges, an open circuit voltage condition is required to exist before the circuit of Figure (3) is completed, [Ref. 3]. Lines 3150 to 3260 determine V_{OC} generated by the solar cell, through the A/D card. Lines 3280 to 3330 then drive the output of the power supply to a value equal to the cell open circuit voltage.

Verification that the power supply output is within 1.5 millivolts (mV) of the cell V_{OC} is performed within lines 3340 - 3490. The 1.5 mV figure arises as a result of the inherent resolution in the 6825A power supply. For this application the best resolution possible is 1.5 mV which becomes the smallest voltage deviation achievable. If the

difference between the V_{OC} and the power supply output is greater than 1.5 mV, the program loops and again samples V_{OC}, drives the power supply to the appropriate voltage, and then tests the difference. If this loop occurs 5 times then an external problem exists and the program returns control to DOS. The external conditions that might cause this condition are covered in Appendix B.

The next portion of the program prompts the user to close the test/setup switch and complete the test circuit. At this time the circuit current should be nearly zero and is measured in lines 3630 - 3650. If the current is negative, the power supply is supplying current and the solar cell is sinking power (an undesirable condition). The power supply output is stepped 1.5 mV lower, and the current is again sampled to verify a zero or small positive value. If this condition still does not exist, then an additional 1.5 mV is subtracted. This process continues until a zero or small (nominally 0.5 milliamps) positive current exists, and the program then prompts the user to close the test/setup switch and complete the test circuit.

The next portion of the cell test subroutine is the data acquisition routine. It is composed of 4 separate modules, three of which contain instructions to measure cell voltage and current, calculate the cell´s power at the data

point, and downstep the power supply. The fourth module allows for a transient-free disconnect.

The first module (lines 3730 - 4020) measures the cell parameters from V_{OC} to 70 % of V_{OC}. As shown in Figure (2), this interval includes the maximum power point for the cell. Since the slope of the curve is steep in this region, the power supply steps in 3 mV increments.

The second module (lines 4030-4260) is identical to the first except that it operates between the 70 % and the 3 % V_{OC} points. The curve is relatively flat here and thus the program steps in 23 millivolt steps to reduce test time.

Each of the first two modules contain a delay loop (lines 3970 - 4000 and 4210 - 4240) to allow a settling time (approximately 40 milliseconds) between measurements.

The third module (lines 4270 - 4470) operates from the 3 percent point to the point at which the measured cell voltage is less than or equal to zero, that is, the cell short circuit current value. This module also steps in 3 mV increments.

The fourth module (lines 4490 - 4600) drives the power supply back to an open circuit voltage condition; V_{OC} is required for a transient free disconnect. The test circuit is opened by the operator, and the program returns the power supply to a zero volts output condition (this is a turn-on/turn-off requirement for the power

supply). The remainder of the fourth module (lines 4730-4780) determines the maximum power, maximum voltage, and maximum current point. Lines 4790 - 4880 calculate 3 significant digits for the cell parameters.

3. Output Routines

The output portion of the program comprises five subroutines. The first, lines 4910 - 5010, prints the voltage, current, and power at each data point measured onto the color monitor, or, by using the control-print screen keys, the data may be printed on the Epson printer for a permanent copy.

The second subroutine, lines 5030 - 5150, plots the solar cell I-V curve on the color monitor. This provides a fast, graphic presentation of the cell characteristics.

The third subroutine is the plotting routine for use with the Hewlett Packard 7475A plotter and is found within lines 5170 to 5970. This routine draws a border, axes, labels, and plots the characteristic I-V curve. The numerical parameters for the cell as well as identifying data are included as well. Several questions are posed to the operator during this routine to allow for multiple plots on a common set of axes. This allows an I-V curve for an irradiated cell to be drawn on the same axes as an I-V curve for the same un-irradiated cell. This feature requires the use of the floppy disk read subroutine as discussed above.

The fourth output subroutine writes the cell voltage, current, and power at each data point measured to a floppy disk. This allows a permanent record of cell data to be maintained. The subroutine also includes writing the cell ID and size to the floppy disk. This routine is found within lines 5990 - 6120.

The last output subroutine prints the calculated parameters of the solar cell on the CRT display. This allows a rapid determination of the cell V_{OC}, I_{SC}, maximum power, voltage and current point, as well as the cell fill factor and efficiency. This routine may be inspected in lines 6140 - 6300.

IV. PRE-IRRADIATION DISCUSSION

A. CELL SELECTION

Production run gallium arsenide solar cells were desired as test specimens for the irradiation experiments. As opposed to a limited production run cell (i.e., those specifically designed and manufactured for experimental use only), irradiation of production run cells could be expected to provide more general results for a specific design. The difficulty found in this approach was that none of the major manufacturers contacted were producing gallium arsenide cells in production quantities at the time cell selection was made.

The Applied Solar Energy Corporation (ASEC), was apparently the closest to producing a "production" cell and thus 20 gallium arsenide cells were ordered. ASEC supplied complete I-V characteristics for each cell as a means of comparison. These 20 cells were specified to have an efficiency of 16% or greater. ASEC also supplied 5 "control" cells, that had a stated efficiency between 15 and 16 per cent. Table 4-1 provides complete technical data for these 2 by 2 centimeter solar cells. Figure (5) is a cross sectional view for this particular cell.

TABLE 4-1

ASEC P/N 2 x 2 centimeter GaAs SOLAR CELLS

Substrate thickness	300 uM
N layer thickness	9 uM
P junction layer thickness-Zn doped	0.5 uM
P window - $Al_xGa_{1-x}As$ ($x \sim .86-.9$) thickness	0.1 uM
P contact material	Au - Zn - Ag
N contact material	Au - Ni - Ge - Ag
Anti-reflection coating	TiO_2, Al_2O_3

[From Reference (4)]

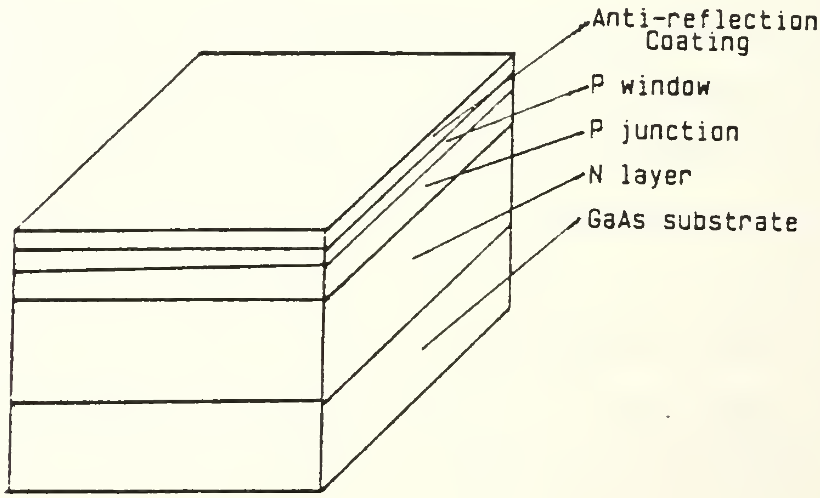


Figure 5. Cross-Sectional View for the ASEC AlGaAs-GaAs Used in this Report.

B. PRE-IRRADIATION CELL TESTS

Current-voltage characteristics for each solar cell were generated, recorded on floppy disks, plotted, and then compared with the ASEC data. The results were within 1 % of the supplied data and are tabulated in Table 4-2. Appendix D contains the graphical I-V characteristics prior to irradiation for each cell tested. The temperature for all tests was 28 degrees (+/- 0.5 degrees) Celsius.

TABLE 4-2

CELL CHARACTERISTICS (PRE-IRRADIATION)
(measurements made @ 28 degrees Celsius)

Cell ID	Voc mV	Isc mA	Pmax mW	Vmax mV	Imax mA	FF	Eff %
ASEC 2	985	117	89	815	109	.772	16.5
ASEC 3	993	115	89	817	110	.782	16.6
ASEC 4	990	116	88	816	108	.767	16.3
ASEC 5	963	120	90	797	113	.776	16.6
ASEC 6	983	117	89	825	108	.773	16.4
ASEC 7	982	118	89	808	110	.767	16.5
ASEC 8	975	116	89	806	111	.786	16.5
ASEC 9	948	119	89	799	111	.787	16.4
ASEC 10	957	116	89	810	110	.803	16.5

V. TEST PROGRAM

A. LINEAR ACCELERATOR DESCRIPTION

The Naval Postgraduate School Linear Accelerator (LINAC) is a traveling wave type accelerator useful for experimenting with electron energies ranging from 20 to 100 million electron volts (MEV). The average current in the electron beam is 0.1 microamperes and has a pulse frequency of 60 Hertz. More detailed descriptions of the linear accelerator may be found in the bibliography.

B. SOLAR CELL IRRADIATION FIXTURE

Figure (6) is a photograph of the test fixture constructed for this experiment with the three test stations filled. The aluminum fixture supports a phenolic rectangle which in turn holds 3 pairs of cell retaining blocks. The retaining block system was designed to allow accurate, repeatable placement of the solar cells as well as minimizing the possibility of cell breakage.

Between the first and second test stations is an area devoted to a phosphorus target. This target provides a visual means of focusing the electron beam onto the cell area.

C. IRRADIATION PROCEDURES

The solar cells to be irradiated were placed in the test fixture which was then stationed in the LINAC vacuum

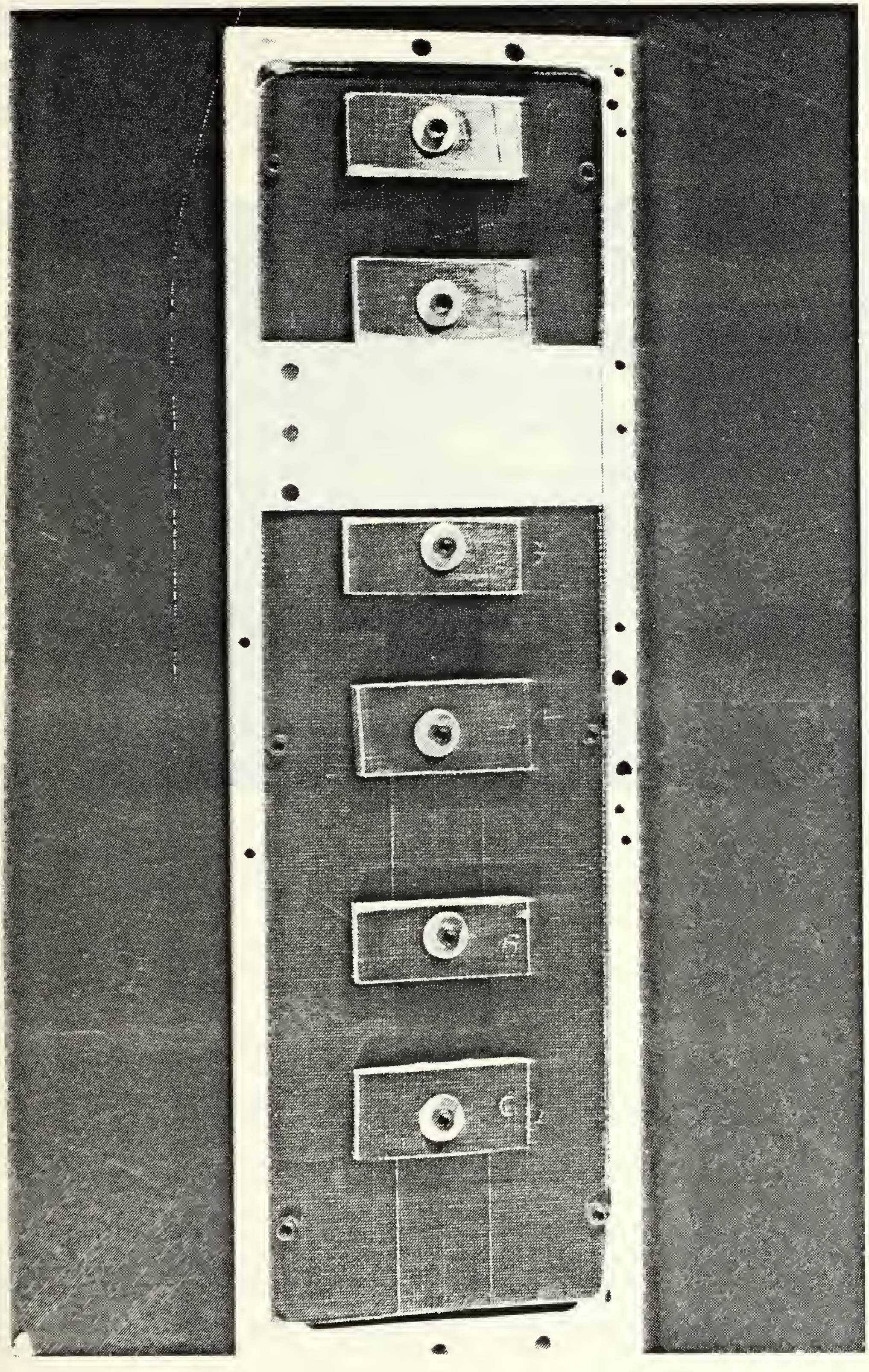


Figure 6. Photograph of the Aluminum Irradiation Test Fixture, Showing 3 Cells in the Test Stations and the Phosphorus Target.

chamber, Figure (7). A vacuum of 6.5×10^{-8} atm was established and an electron energy level was selected. The LINAC was then operated for the time required to achieve

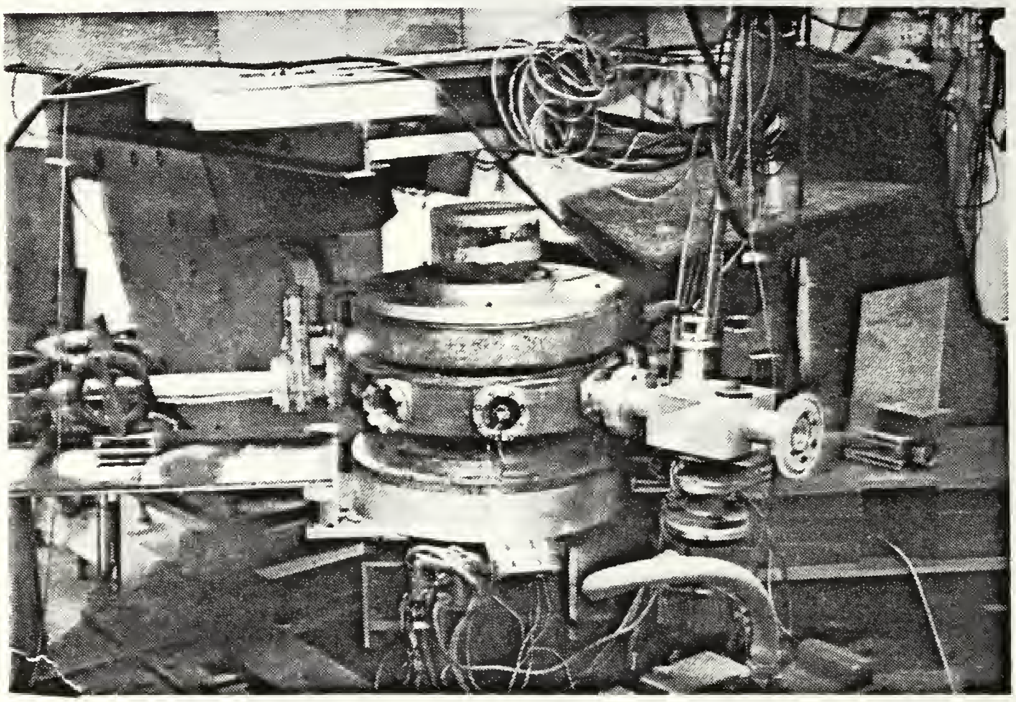


Figure 7. Photograph of the LINAC Target Chamber (center)

the desired electron fluence. The electron fluences used ranged from 1×10^{12} electrons/cm^2 to 1×10^{15} electrons/cm^2 at increasing values of 10^1 e/cm^2 for each successive test. Each cell was irradiated at an electron energy of 20 MEV. This energy was chosen since data are not currently available for degradation at this level; further, 20 MEV is the lower effective limit of the LINAC energy spectrum.

The fluence that a cell receives during a test is determined by the time that the electron beam is turned on. This time is measured by monitoring the charge deposited on a capacitor. Using the relationship

$$Q = C \times V \tag{6}$$

where Q = charge (Coulombs)

C = capacitance (Farads)

V = voltage (Volts)

then the voltage across the capacitor may be calculated by

$$V = Q/C \tag{7}$$

Since the total charge deposited on the capacitor equals the fluence, ϕ (e/cm^2), times the electron charge, q_e (coul/e), times the cell area, A (cm^2), then a unique voltage may be calculated for given values of ϕ and C. Algebraically, this equation may be written as

$$V = \frac{\phi \, q_e \, A \, \eta}{C} \tag{8}$$

where the terms have been previously defined. The quantity η is the efficiency of the secondary emissions monitor (SEM) that measures the electron beam current and is numerically equal to 2.6 %. Figure (8) shows the configuration of the LINAC target chamber during the solar cell irradiations. All irradiations were performed at normal

incidence to the cell. Characteristic curves were measured following each irradiation.

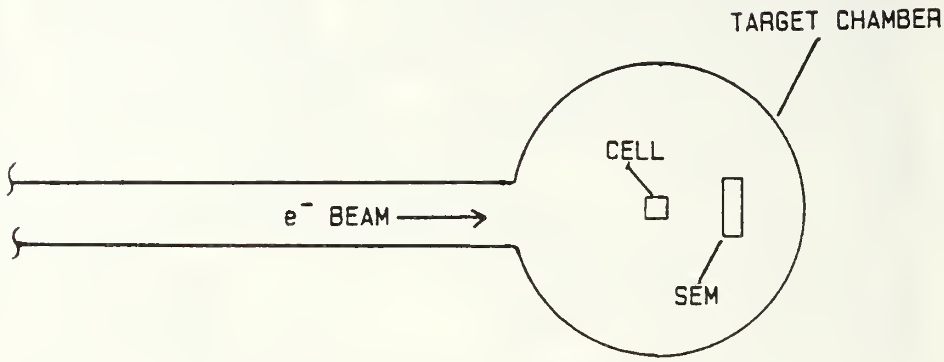


Figure 8. Configuration of Interior of Target Chamber During Solar Cell Irradiation.

VI. DISCUSSION OF TEST RESULTS

A. DAMAGE EQUIVALENT 1 MEV FLUENCE

Table 6-1 lists the calculated mean and standard deviation values for post irradiation cell open circuit voltage, short circuit current, and maximum power as a function of 20 MEV electron fluence.

The tabulated data for the above parameters was next plotted as a function of fluence and may be seen in Figures (9) through (14), at the end of this chapter. Vertical error bars are included to indicate a 2 , 95 % confidence level. The error associated with the fluence value is less than 2 % and is not included on this scale plot.

The 1 MEV equivalent electron fluence concept was then applied to the test results. The fluence values corresponding to a 20 % degradation in V_{OC}, I_{SC}, and P_{max} were determined [Ref. 5: pp. 3.21-3.24;Ref. 6: pp. 5-16]. Next, fluence values corresponding to a 20 % degradation due to 1 Mev energy electron irradiation were extracted from Figures 3.100, 3.102, and 3.103 of Reference (5), for V_{OC}, I_{SC}, and P_{max}. The fluence values extracted were then divided by the 20 MEV, 20 % degradation fluences to arrive at an equivalent damage coefficient for 1 MEV energy electrons. These values are shown in Table 6-2.

TABLE 6-1

CALCULATED MEAN VALUES FOR POST IRRADIATION CELL TESTS

(measurements made at 28 degrees Celsius)
(standard deviations in parenthesis below each parameter)

Fluence (e/cm^2)	Mean V_{oc} (mV)	Mean I_{sc} (mA)	Mean P_{max} (mW)
0	972.3 (17.2)	117.5 (1.9)	88.9 (.57)
10^{12}	964.3 (14.9)	116.4 (1.3)	87 (1.0)
10^{13}	944.6 (12.3)	113.5 (1.9)	82.7 (2.5)
10^{14}	898.3 (7.8)	106.6 (3.0)	73.6 (2.7)
10^{15}	775.3 (16.5)	76.6 (.57)	44.3 (2.1)

TABLE 6-2

EQUIVALENT DAMAGE COEFFICIENTS

Parameter	$\phi(1) / \phi(20)$
V_{oc}	20
I_{sc}	8
P_{max}	3

Thus, if it is desired to determine the fluence of 1 MEV electron radiation required to degrade a parameter to an equivalent degree of 20 MEV radiation, then the 1 MEV fluence need only be multiplied by the factor from the table.

B. ERROR ANALYSIS

The analysis of errors will be discussed in four areas: damage equivalent fluence, Kratos spectral quality, LINAC errors, and data acquisition and computation errors.

1. Damage Equivalent Fluence

If the degradation curves for the 1 MEV [Ref. 5: pp. 3.141-3.144] and the 20 MEV cases are plotted on the same set of axes, it will be noted that they are not parallel, and therefore the concept of equivalent fluence does not strictly apply [Ref. 6: pp. 5-6]. Thus, the equivalent damage coefficient calculated for a 20 % degradation will not equal the coefficient for a 15 or 25 % degradation. The difference, however is small (< 10 %), and may be neglected given the uncertainties associated with outer space electron fluences. Of more important concern is that the gallium arsenide cell used in the figures of Reference (5), is not the same as those used in this thesis. Therefore, further study is required to determine the accuracy of these equivalent damage coefficients for this cell type vs. 1 MEV electrons.

2. Kratos Spectral Quality

A discussion was included in Chapter II concerning the spectral output of the Kratos source. Based on the values of i^{sim}/i^{sun} for the six spectral bands measured, it may be concluded that in a relative sense, the Kratos source is a fair approximation to a solar constant. The fact that the constant is not the same for the shorter and longer wavelength bands indicates that the Kratos source does not provide an equal relative spectral irradiance over those two bands. That this difference occurs does not appear to contribute a significant amount of error, however, since the pre-irradiation cell parameters differ from the supplied ASEC values by an average of 1 %. Thus, the spectral quality of the Kratos source may be considered good.

3. LINAC Errors

The energy in the electron beam is determined by the voltage required by the beam deflection magnets to "steer" the beam onto the target. There is a linear relationship between the deflection magnet voltage and the energy of the electron beam, and it is this linearity that is used to establish an energy of 20 MEV. The error associated with determination of the beam energy using this procedure is less than 2 %.

As discussed in paragraph (A) above, the delivered fluence values for each irradiation could differ from the expected values by less than 2 %.

4. <u>Data Acquisition and Computation Errors</u>

From an examination of any one of the I-V curves in Appendices E or F, it will be noted that the curves are not smooth. This is due to several factors: (a) the inherent resolution of the power supply (1.5 mV); (b) the inherent resolution of the A/D converter (2.5 mV); (c) the averaging of five samples of cell voltage; (d) the 500 Hz sampling frequency; (e) the variations that occur in the lamp power supply causing variations in lamp intensity; and (f) the method of plotting the data.

The resolutions for the power supply and the A/D converter are essentially fixed quantities for the purposes of this solar cell testing system. Although the respective resolutions could be decreased in order to increase the <u>range</u> of the system, they can not be increased beyond their present values using existing components.

The number of samples averaged and the sampling frequency were both determined by extensive testing. Since much of the noise in the system occurs at 60 Hz, the sampling frequency should be greater than 120 Hz. At this frequency however, there was still an unacceptable level of noise present in the data, most easily seen in the graphical presentation. Further, the lower the sampling frequency, or the greater the number of samples averaged, then the greater is the time required to run a parameter test. Thus, a 500 Hz sampling rate and 5 samples were decided upon.

The variations that occur in the lamp intensity are related to the variations in the lamp power supply input voltage. Since the feeder to the 208 volt input circuit is shared by other devices in the building (air compressors, etc.), each time a high current device starts, there is a lowering of the input supply voltage. The deviations seen in the lamp intensity are small, averaging less than 3 % of the full scale value. There may be gross deviations however, which may require running the cell parameter test a second time.

The raw digital values for each data point are input to the HP 7475A plotter to arrive at a final plot. The discrete voltages that the power supply steps through are thus visible in the plots. The step size could be decreased which would minimize the unevenness in the plots, however this would have an adverse effect on the time required to run a test. One alternative would be to input analog values to a plotter which would alleviate some of the unevenness.

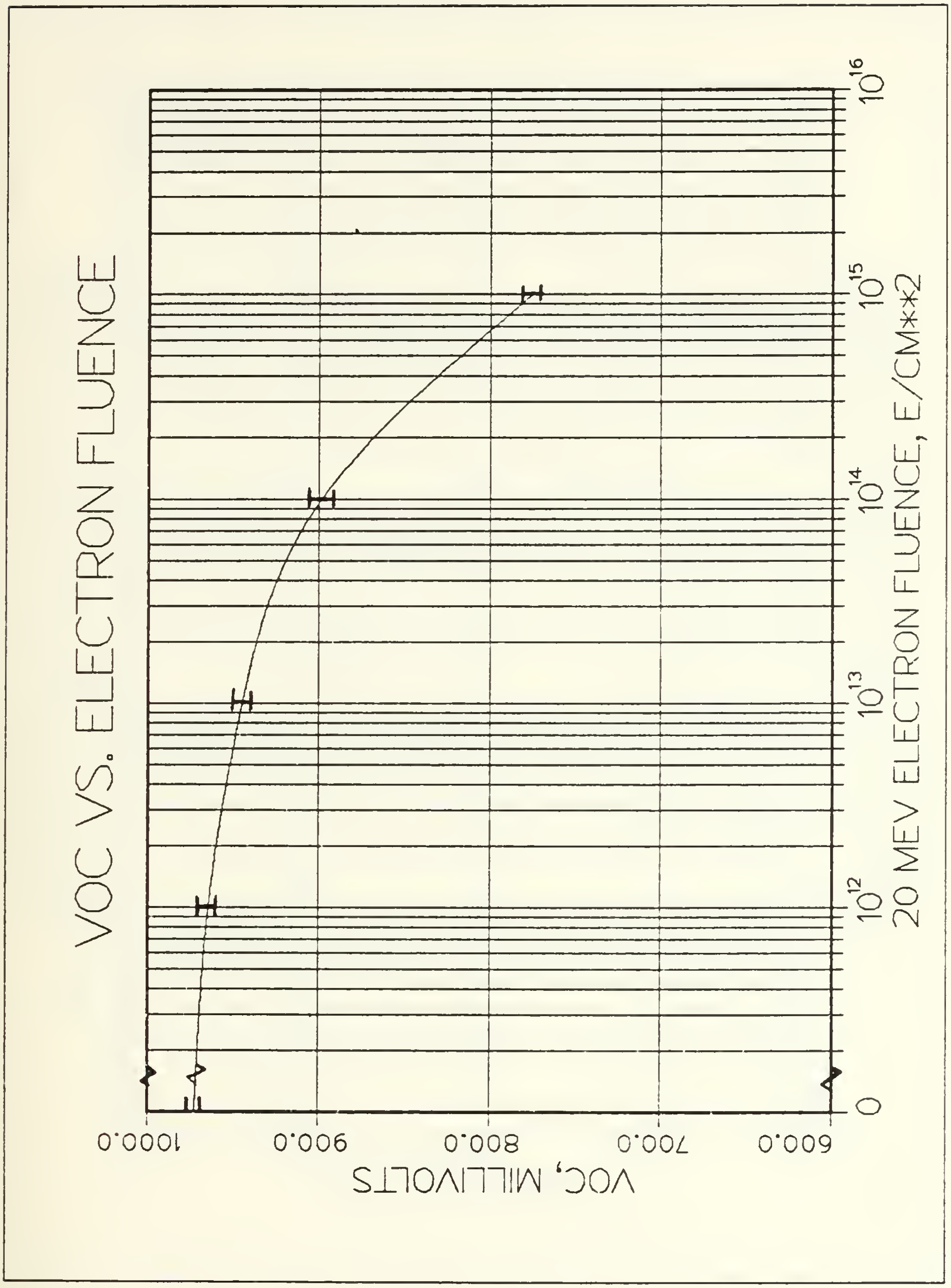


Figure 9. Solar Cell Open Circuit Voltage as a Function of 20 MEV Electron Fluence.

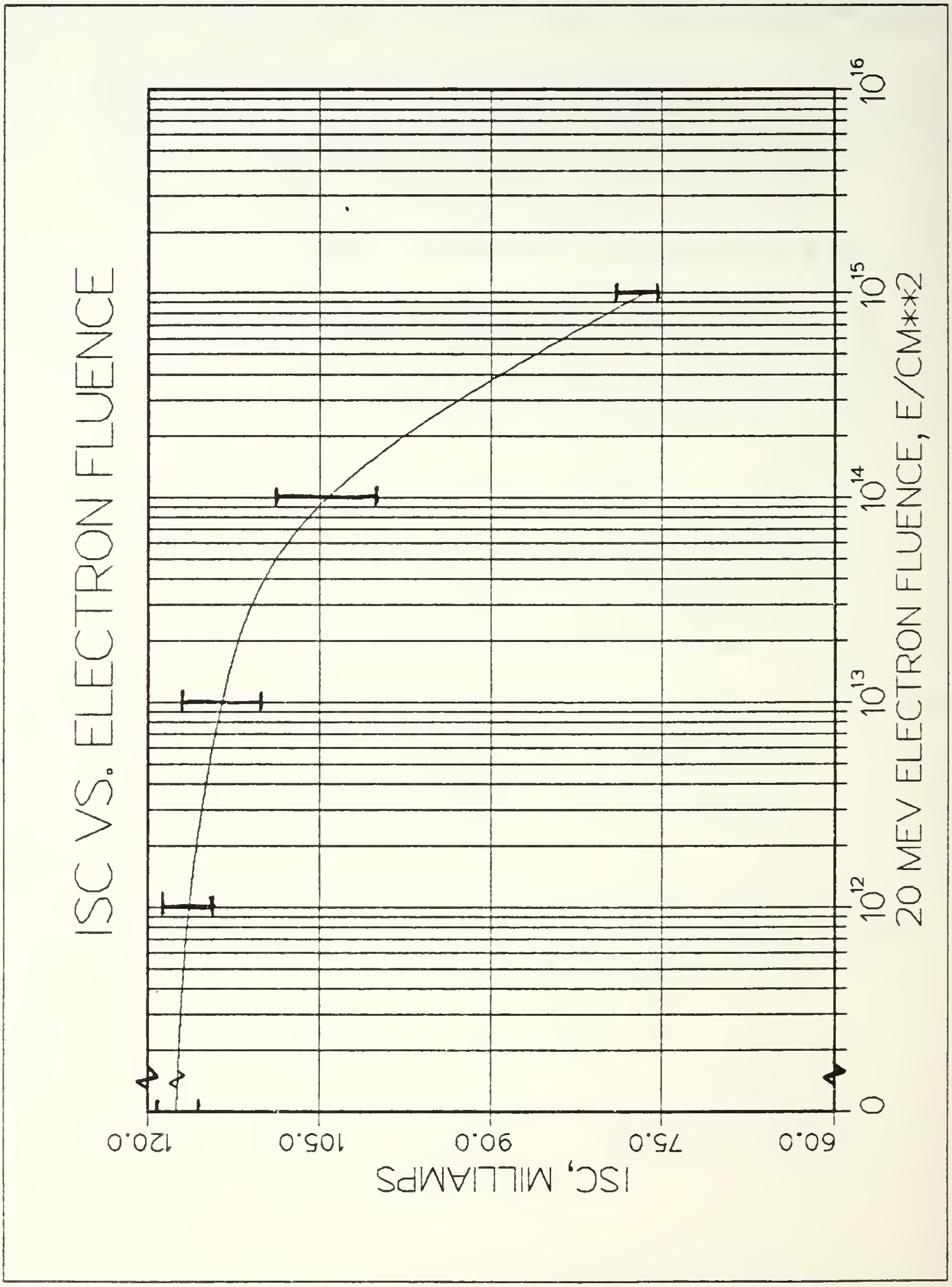


Figure 10. Solar Cell Short Circuit Current as a Function of 20 MEV Electron Fluence.

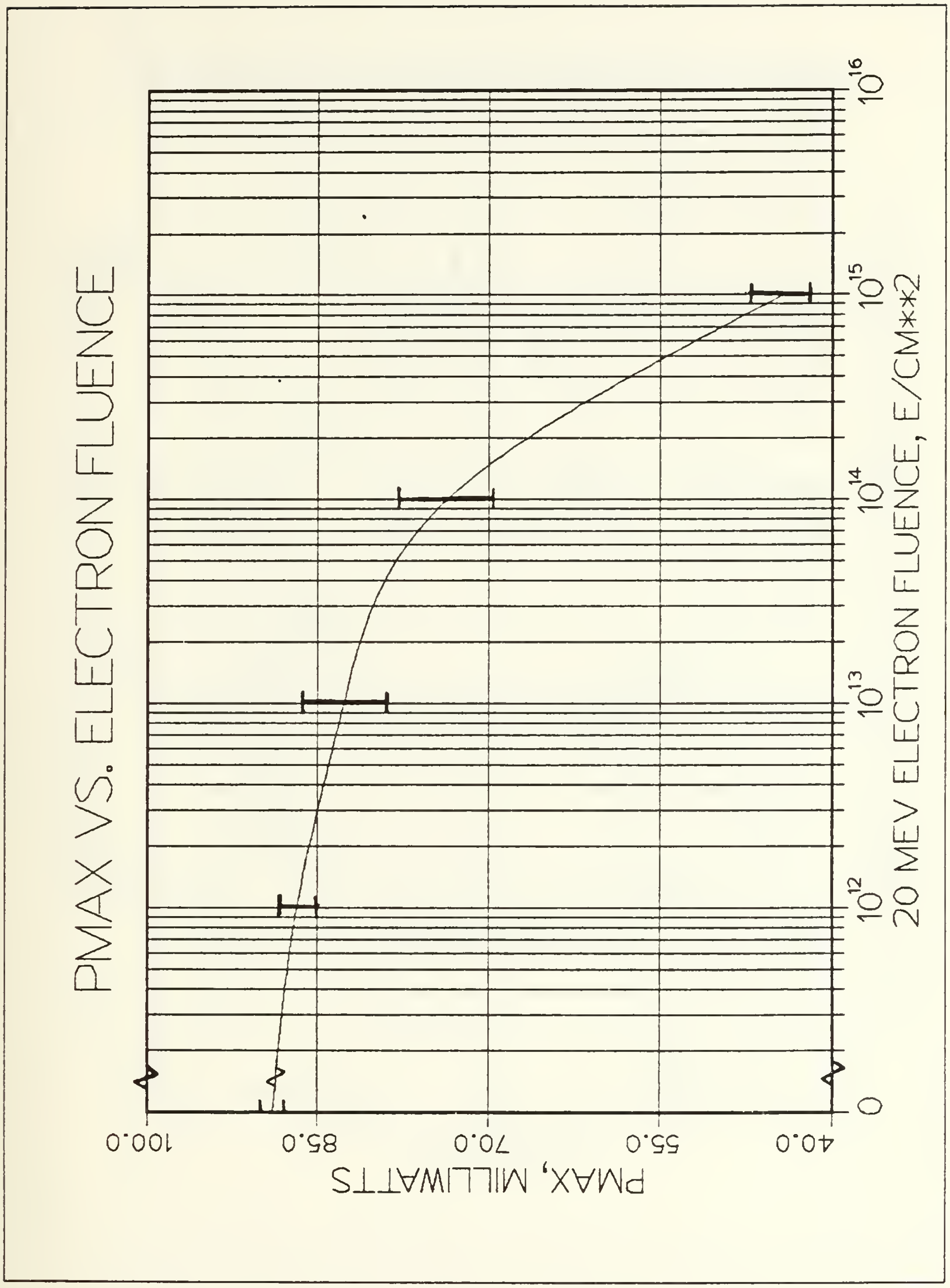


Figure 11. Solar Cell Maximum Power as a Function of 20 MEV Electron Fluence.

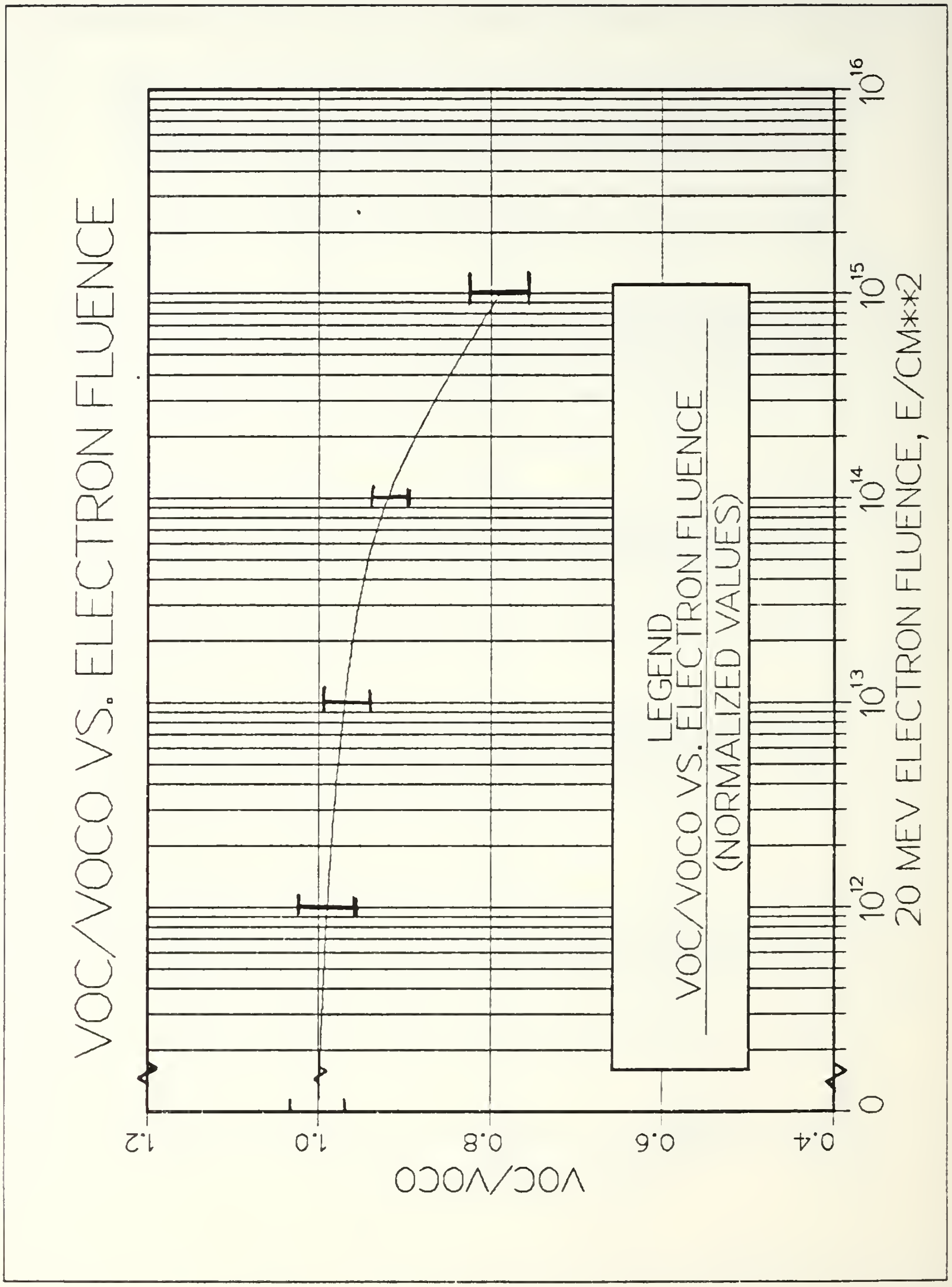


Figure 12. Normalized Open Circuit Voltage as a Function of 20 MEV Electron Fluence.

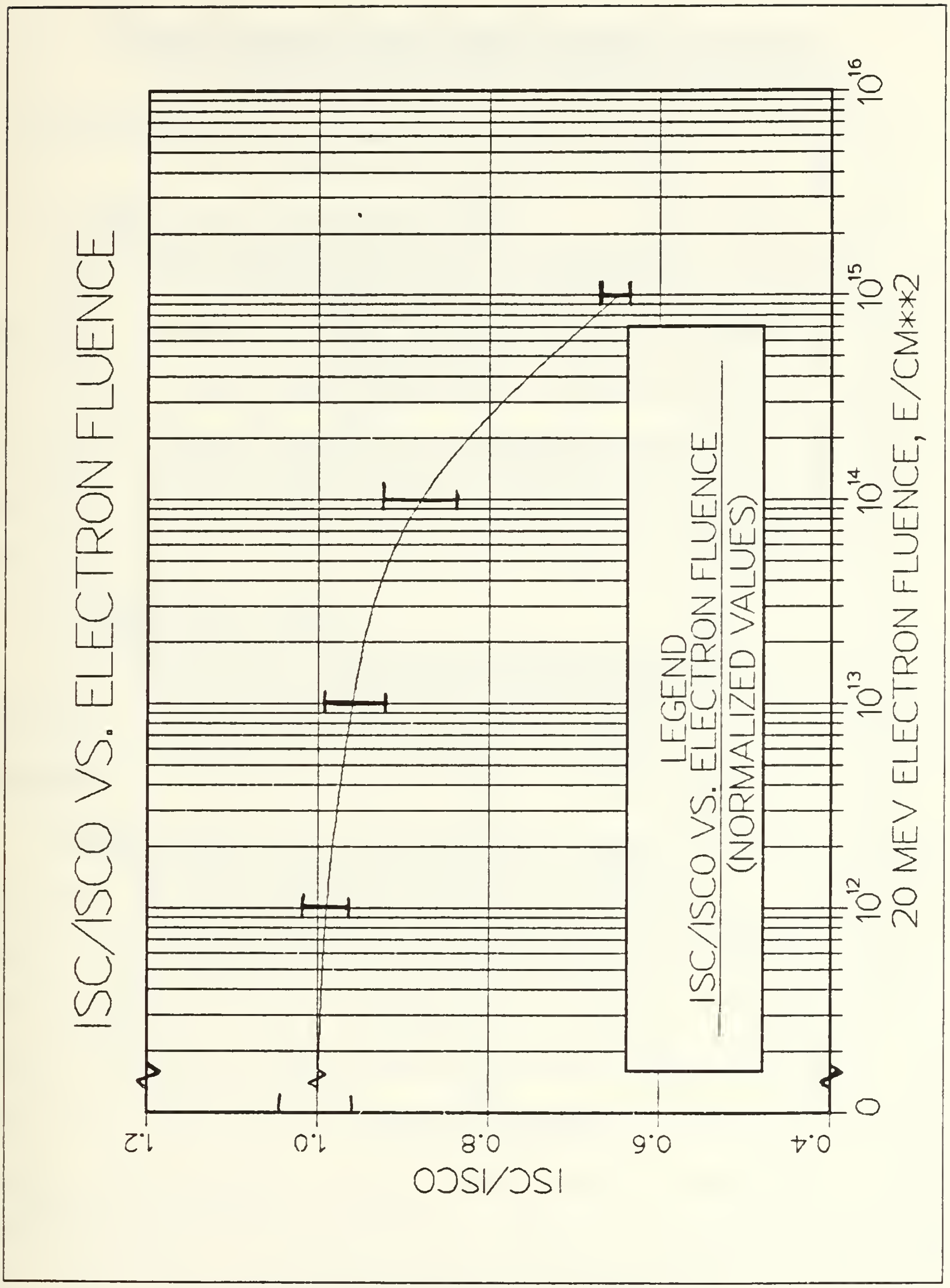


Figure 13. Normalized Short Circuit Current as a Function of 20 MEV Electron Fluence.

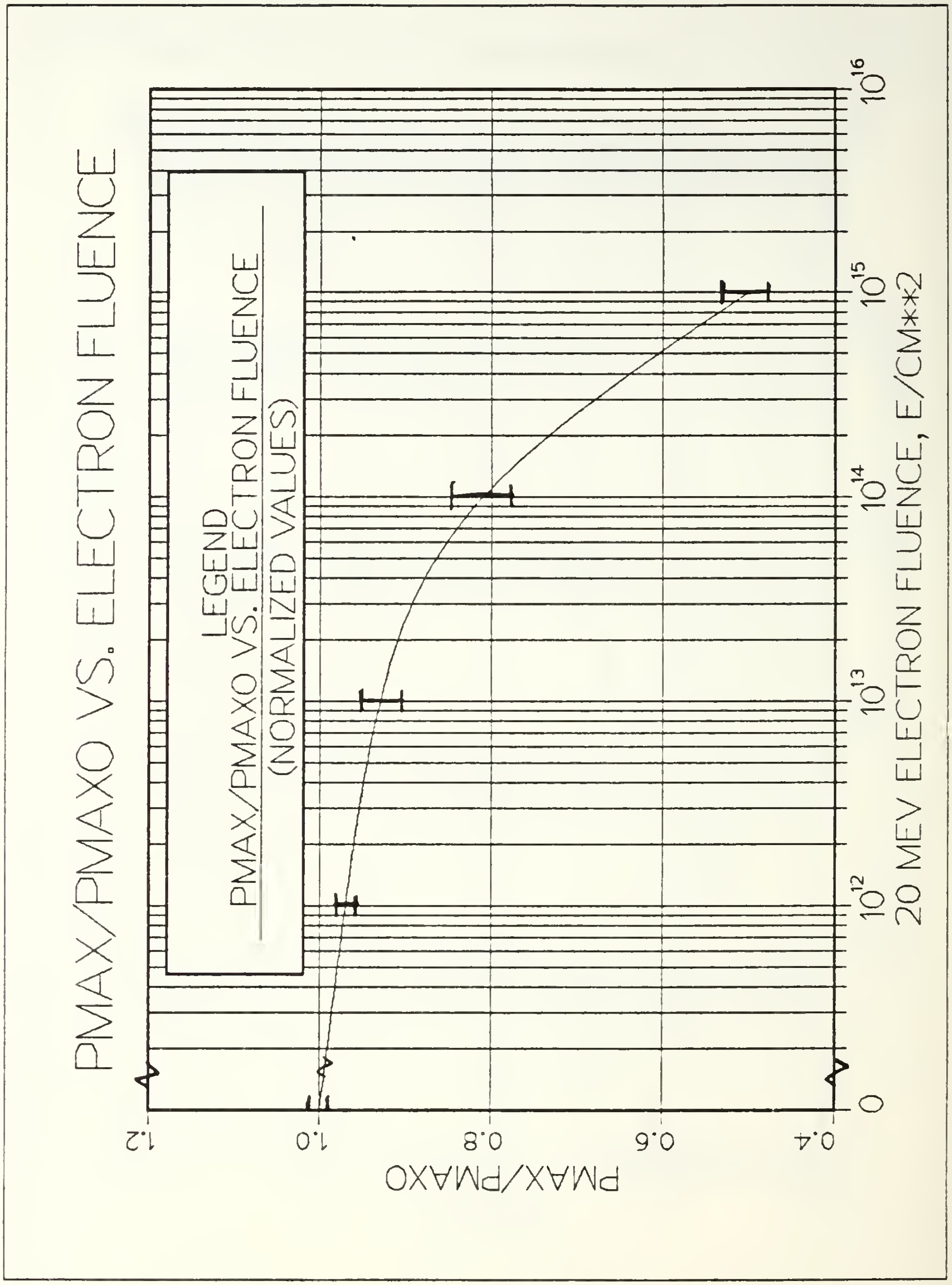


Figure 14. Normalized Maximum Power as a Function of 20 MEV Electron Fluence.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Solar Cell Testing System

Based on the excellent correlation between the ASEC measured parameters for the 25 gallium arsenide cells and the results obtained using the automated solar cell test routine, it is apparent that the solar cell laboratory provides an accurate, repeatable means of determining solar cell parameters.

2. Radiation Damage

It was found that the average maximum power output decreased by 50 % following a cumulative irradiation by electrons to a total fluence of 1×10^{15} e/cm^2.

The results of the post-irradiation testing (Table 6-1) and the equivalent damage coefficients calculated (Table 6-2), appear reasonable based on published data for lower electron energy degradation tests. Depending on the results of 1 MEV electron irradiation for this particular ASEC cell, the equivalent damage coefficients may require revision either up or down. Until this is accomplished and data published, a conservative approach should be taken when using these equivalent damage coefficients.

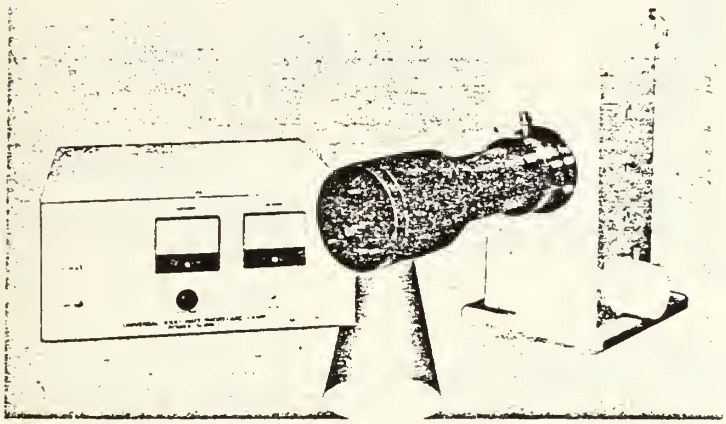
B. RECOMMENDATIONS

It is recommended that data be obtained for 1 MEV electron radiation degradation to these particular ASEC solar cells. This would enable the computation of more accurate equivalent damage coefficients.

APPENDIX A

TECHNICAL SPECIFICATIONS

TECHNICAL SPECIFICATIONS FOR THE KRATOS SS 2500 SOLAR SIMULATOR SYSTEM



The ideal Solar Simulator for any number of applications. Rain or shine.

Our Solar Simulators have found widespread acceptance—in a variety of applications—owing to their dependability, accuracy, convenience and economy. Here are just a few areas of use:

- Cosmetics and Dermatology (erythema studies, sunscreen testing, etc.)
- Solar Energy (solar cell development, solar collectors, etc.)
- Biodegradation/Solar Exposure Durability Testing
- Artificial Aging and Weathering
- Aerospace
- Medicine and Dentistry
- Environmental Simulation Chambers

Five models up to 7000W.

From the relatively compact 150W system, up to the powerful 7000W system, with a 1000W, 2500W and 1000W ellipsoidal system in-between, we have the Solar Simulator that is right for your application.

Built for performance; Priced for value.

Our Solar Simulators have been designed based on existing illumination system technology—the standard for excellence. The result is a product of proven performance, at a cost within the reach of most lab budgets.

System components—lamphousing, optics, and lamp power supply—are manufactured under rigorous quality standards, ensuring optimum long term performance. Routinely.

Reproducible illumination conditions every time you turn it on.

The Xenon Arc Lamp is known for its color constancy throughout its operating lifetime. So the tests done with our Solar Simulator—even if months apart—will be done under identical illumination (try that with the sun itself!). The result is better control over your testing, and ultimately, more valid results.

Controlled spectral output.

Carefully selected optics and filters produce refined spectra closely following those of the accepted Air Mass O (AMO), AM1, and AM2 standards for solar radiation outside the atmosphere (AMO) and at ground level (AM1, AM2).

Reduced heat output.

The spectral filtering employed in all three Solar Simulators effectively attenuates the intense infrared output produced by the unfiltered Xenon arc, without distorting the desired Air Mass values. This minimizes problems associated with IR burns in cosmetic and dermatological studies, and excessive heat buildup during solar cell testing, aerospace studies, or other investigations.

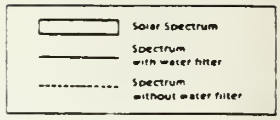
In applications where additional IR heat filtering is desired, such as high intensity illumination in cosmetic or dermatological studies, a special dichroic mirror may be used in the beam deflection tube to produce an IR-free output.

Intensity equivalent to several, even many, suns. Or, one sun at a time.

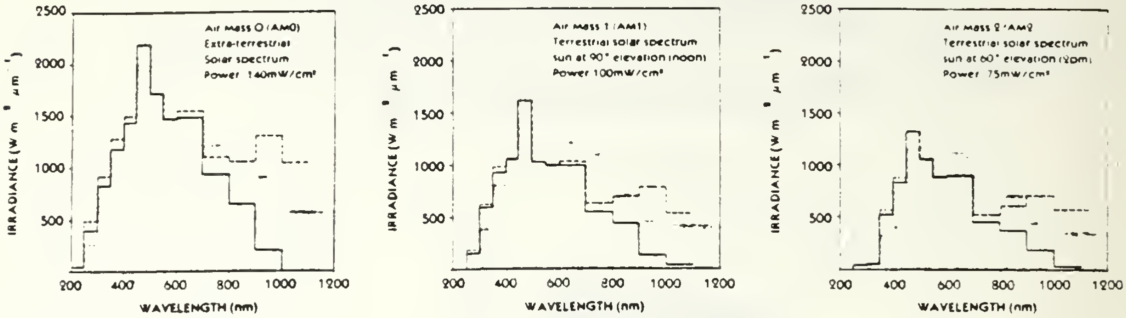
By moving the illuminated subject closer to the source, you can effectively "concentrate" the unit's power over a smaller area . . . with an intensity equivalent to that of more than 50 suns! For applications such as sunscreen testing and artificial aging, this capability greatly reduces necessary exposure times.

For other applications, such as solar cell testing, where hyper-illumination is impractical, the SS1000 provides one solar constant at AMO over a 8 inch diameter circle; SS2500 over a 12 inch circle; SS5000 over a 16 inch circle.

Figure 15. Technical Specifications for the Kratos SS 2500 Solar Simulator System. [Ref. 7: pp. 34-35]



Spectral Distribution and Output Intensity Data



Illuminated Spot Dia.		Number of Suns at AM0 Intensity and Spectrum		
in	cm	SS1000	SS2500	SS5000
4	10.2	4.5	11.3	22.6
6	15.2	2.0	5.1	10.3
8	20.3	1.1	2.8	5.7
10	25.4	0.7	1.7	3.4
12	30.5	0.5	1.1	2.3
14	35.6	0.3	0.8	1.7

Illuminated Spot Dia.		Number of Suns at AM1 Intensity and Spectrum		
in	cm	SS1000	SS2500	SS5000
4	10.2	6.1	15.1	30.2
6	15.2	2.7	6.8	13.7
8	20.3	1.5	3.8	7.6
10	25.4	0.9	2.2	4.4
12	30.5	0.6	1.5	3.0
14	35.6	0.4	1.1	2.2

Illuminated Spot Dia.		Number of Suns at AM2 Intensity and Spectrum		
in.	cm.	SS1000	SS2500	SS5000
4	10.2	[illegible]	19.3	38.6
6	15.2	3.5	8.7	17.5
8	20.3	1.9	4.8	9.7
10	25.4	1.1	2.7	5.4
12	30.5	0.8	1.9	3.8
14	35.6	0.6	1.4	2.9

Note The data presented above represents typical performance Exact specification depends upon conditions of operation

Caution Ultraviolet and infra-red radiation is known to be harmful The use of this equipment for irradiating human subjects is entirely at the risk and liability of the buyer or user

Reliable, Convenient; Easily operated

Obviously more reliable and convenient than the sun itself, the Xenon Arc Lamp and Power Supply System is among the most dependable and stable sources available. Routine operation of a Solar Simulator is extremely straightforward, and apart from simple lamp replacement (only about every 1000 hours of operation), the Solar Simulator is virtually maintenance-free.

A modular system that changes with changing needs.

Our Solar Simulators provide the flexibility of modular design. As needs change, the system can be changed, without requiring investment in a new system.

The SS1000 can be used with any lamp from 250 to 1000W for small-scale applications, less powerful lamps provide a certain degree of economy in replacement.

The SS2500 and SS5000 can be used with any lamp from 1000 to 7000W, requiring only minor changes in lamp sockets and system cooling configuration.

Standard Solar Simulator

Our Solar Simulators include all needed components for operation. Xenon arc lamp, lamp heat sinks (not req d on SS 1000), lamp sockets, lamp power supply, lamp housing, all optics, filter holder, complete set of air mass filters, 90° beam deflection mirror, and flexhose for ozone removal.

SS 1000 – 1000W Solar Simulator
Complete as described above; includes LH 151 Lamp Housing and LPS 255 HR Lamp Power Supply. Lamps from 250 to 1000W may be used. Water filter (for IR attenuation) optional.

SS 2500 – 2500W Solar Simulator
Complete as described above; includes LH 152 Lamp Housing and LPS 400 Lamp Power Supply. Lamps from 900-6500W may be used (with addition of certain accessories). Includes water filter.

SS 5000 – 5000W Solar Simulator
Complete as described above; includes LH 152 Lamp Housing, LPS 400 Lamp Power Supply, and 2 auxiliary fans for lamp cooling. Lamps from 900-6500W may be used. Includes water filter.

The design of the lamp housings and power supplies of these Solar Simulator Systems permits the use of a variety of different lamps, as indicated above.

Additionally, for very small scale applications, a 150W Solar Simulator is also available.

Accessories

As indicated above, each Solar Simulator System is completely ready for operation at any of the air mass standards: AM0, AM1, or AM2. For conventional applications, no other accessories are required.

However, in certain applications, it may be desirable to modify the spectrum in some way or choose from among several options.

For example, a dichroic mirror may be used in the 90° beam deflection tube, to reflect the UV and visible light, while dissipating the infrared. Such a mirror is useful when multiple suns in the UV and visible are required but additional heat (infrared) is undesirable. Several reflection/transmission spectral profile curves are available; consult us with your application.

Additionally, electronic shutters, variable iris diaphragms, square beam masks and other accessories are also available.

Figure 15. Technical Specifications for the Kratos SS 2500 Solar Simulator System. (continued)

TECHNICAL SPECIFICATIONS FOR THE HEWLETT-PACKARD MODEL 3478A MULTIMETER

DC VOLTAGE

Input Characteristics:

Range	Maximum Reading (5½ Digit)	Resolution 5½ Digit	4½ Digit	3½ Digit
30mV	±30.3099mV	100nV	1μV	10μV
300mV	±303.099mV	1μV	10μV	100μV
3 V	±3.03099 V	10μV	100μV	1mV
30 V	±30.3099 V	100μV	1mV	10mV
300 V	±303.099 V	1mV	10mV	100mV

Input Resistance:

30mV, 300mV, 3V ranges >$10^{10}\Omega$
30V, 300V ranges 10MΩ ± 1%

Maximum Input Voltage: (non-destructive)

Hi to Lo: 303V rms or 450V peak
Hi or Lo to Earth Ground ±500V peak

Measurement Accuracy:

±(% of reading + number of counts)
Auto-zero ON

5½ Digit Mode:

Range	Cal. Temp ± 1°C 24 Hours	Cal Temp. ±5°C 90 Day	1 Year
30mV	0.027 + 35	0.030 + 41	0.040 + 41
300mV	0.005 + 4	0.007 + 5	0.020 + 5
3 V	0.0034 + 2	0.006 + 2	0.019 + 2
30 V	0.005 + 3	0.007 + 2	0.020 + 3
300 V	0.0055 + 2	0.008 + 2	0.020 + 2

4½ and 3½ Digit Mode:

Accuracy is the same as 5½ digit mode for % of reading; use 1 count for number of counts on all ranges except 30mV range use 4 counts.

The Cal. Temp. (Calibration Temperature) is the temperature of the environment where the 3478A was calibrated. Calibration should be performed with the temperature of the environment between 20°C and 30°C.

Auto Zero Off:

(5½ digit) for a stable environment (±1°C) for < 24 hrs., add 10 counts to accuracy specification for 30mV range, 11 counts for 300mV and 30V ranges, 3 counts for 3V and 300V range.

Temperature Coefficient:

0°C to 55°C
5½ digit display, auto zero ON
±(% of reading + number of counts)/°C

Range	Temperature Coefficient
30mV	0.0028 + 5.0
300mV	0.0005 + 0.5
3 V	0.0004 + 0.05
30 V	0.0006 + 0.5
300 V	0.0004 + 0.05

Noise Rejection:

In dB, with 1kΩ imbalance in Lo lead. AC rejection for 50/60Hz ± 0.1%. Auto-zero ON.

Display	AC NMR	AC ECMR	DC CMR
5½ digits	80	150	140
4½ digits	59	130	140
3½ digits	0	70	140

Maximum Reading Rates: (readings/sec)

First reading is correct when triggered coincident with step input.

The reading rates are dependent on the speed of the controller being used.

Line Frequency	Auto Zero	Resolution 3½ Digits	4½ Digits	5½ Digits
60Hz	Off	71	33	4.4
	On	53	20	2.3
50Hz	Off	67	30	3.7
	On	50	17	1.9

AC VOLTAGE (true rms responding)

Input Characteristics:

Range	Maximum Reading 5½ Digit	Resolution 5½ Digit	4½ Digit	3½ Digit
300mV	303.099mV	1μV	10μV	100μV
3 V	3.03099 V	10μV	100μV	1mV
30 V	30.3099 V	100μV	1mV	10mV
300 V	303.099 V	1mV	10mV	100mV

Input Impedance:

1MΩ ± 1% shunted by < 60pF

Maximum Input Voltage: (non-destructive)

Hi to Lo: 303V rms or 450V peak
Hi or Lo to Earth Ground ±500V peak

Measurement Accuracy:

±(% of reading + number of counts)
Auto zero ON, 5½ digit display. Accuracy is specified for sinewave inputs only > 10% of full scale.
1 Year, Cal. Temp. ±5°C

Frequency	Ranges 300mV	3V 30V	300V
20Hz-50Hz	1.14 + 163	1.14 + 102	1.18 + 102
50Hz-100Hz	0.46 + 163	0.46 + 103	0.50 + 102
100Hz-20kHz	0.29 + 163	0.26 + 102	0.33 + 102
20kHz-50kHz	0.56 + 247	0.41 + 190	0.55 + [illegible]
50kHz-100kHz	1.74 + 882	1.05 + 325	1.26 + 825
100kHz-300kHz		10.1 + 3720 (30V Range Only)	

Figure 16. Technical Specifications for the Hewlett-Packard Model 3478A Multimeter. [Ref. 8: pp. 1.2-1.4]

Auto Zero Off:

(5½ digits) for a stable environment (± 1°C), for < 24 hrs., add 10 counts to accuracy specifications for all ranges

Temperature Coefficient:

0°C to 55°C
5½ digit display, auto-zero ON
For frequencies < 20kHz, ±(0.016% of reading + 10 counts)/°C
For frequencies > 20kHz, ±(0.04% of reading + 10 counts)/°C

Crest Factor:

>4:1 at full scale.

Common Mode Rejection:

With 1kΩ impedance in Lo lead, >70dB, at 60Hz

Maximum Reading Rates: (readings sec)

First reading is correct within 70 counts of final value when on correct range, triggered coincident with step input. Add 0.6 seconds for each range change.

Reading rates are the same as dc volts using fast trigger (T5). Using Normal Trigger (T1, T2, T3):

For 50 or 60Hz operation, auto-zero ON or OFF
3½ or 4½ digits 1.4
5½ digits 1.0

RESISTANCE (2-wire Ω, 4-wire Ω)

Input Characteristics:

Range	Maximum Reading (5½ Digit)	Resolution 5½ Digit	4½ Digit	3½ Digit
30 Ω	30.3099 Ω	100 μΩ	1mΩ	10mΩ
300 Ω	303.099 Ω	1mΩ	10mΩ	100mΩ
3 kΩ	3.03099 kΩ	10mΩ	100mΩ	1 Ω
30 kΩ	30.3099 kΩ	100mΩ	1 Ω	10 Ω
300 kΩ	303.099 kΩ	1 Ω	10 Ω	100 Ω
3MΩ	3.03099MΩ	10 Ω	100 Ω	1 kΩ
30MΩ	30.3099MΩ	100 Ω	1 kΩ	10 kΩ

Input Protection (non-destructive)

Hi source to Lo source ±350V peak
Hi sense to Lo sense ±350V peak
Hi or Lo to Earth Ground ±500V peak

Measurement Accuracy:

±(% of reading + number of counts)
Auto zero ON, 4-wire ohms
Maximum INPUT LO impedance is 3.3% of full scale

5½ Digit Mode

Range	Cal Temp ± 1°C 24 Hours	Cal Temp ±5°C 90 Day	1 Year
30Ω	0.023 + 35	0.027 + 41	0.034 + 41
300Ω	0.0045 + 4	0.012 + 5	0.017 + 5
3k – 300kΩ	0.0035 + 2	0.011 + 2	0.016 + 2
3 MΩ	0.0052 + 2	0.011 + 2	0.016 + 2
30MΩ	0.036 + 2	0.066 + 2	0.078 + 2

Note

>30 M ohm Range accuracy is approximately 0.002% M ohm

2 Wire Ohms Accuracy:

Same as 4-wire ohms except add a maximum of 200mΩ offset. On the 3M ohm Range, add .0016% of reading and on the 30M ohm Range, add .0083%

Auto-Zero Off:

(5½ digit) for a stable environment (± 1°C) for < 24 hrs., add 110 counts to accuracy specification for 30Ω range, 11 counts for 300Ω, 3 counts for 3KΩ through 300KΩ ranges, 8 counts for 3MΩ range, and 33 counts for 30MΩ range

Temperature Coefficient:

0°C to 55°C
5½ digit display, auto-zero ON
± (% of reading + number of counts)/°C

Range	Temperature Coefficient
30Ω	0.003 + 5
300Ω	0.0009 + .5
3k – 300kΩ	0.0009 + .05
3MΩ	0.0021 + .05
30MΩ	0.021 + .05

Current Through Unknown:

Range	Current
30 ohm	1mA
300 ohm	1mA
3K ohm	1mA
30K ohm	100μA
300K ohm	10μA
3M ohm	1μA
30M ohm	100nA

Maximum Open Circuit Voltage:

6.5V

Maximum Reading Rates:

Same as dc volts except for 3MΩ and 30MΩ ranges. For 3MΩ range, add 30ms, for 30MΩ range, add 300ms per reading

DC CURRENT

Input Characteristics

Range	Maximum Reading (5½ Digit)	Resolution 5½ Digit	4½ Digit	3½ Digit
300mA	± 303.099mA	1μA	10μA	100μA
3 A	± 3.03099 A	10μA	100μA	1mA

Maximum Input: (non-destructive)

3A from < 250V source, fuse protected

Measurement Accuracy:

± (% of reading + number of counts)
Auto zero ON, 5½ digit display

Range	Cal Temp. ±5°C 90 Days	1 Year
300mA	0.11 + 40	0.15 + 40
3A (<1A input)	0.14 + 5	0.17 + 5
3A (>1A input)	1.0 + 30	1.0 + 30

Figure 16. Technical Specifications for the Hewlett-Packard Model 3478A Multimeter (continued)

Auto Zero Off:

(5½ digit) for a stable environment (± 1°C), for < 24 hrs., add 110 counts to accuracy specification for 300mA range, 11 counts for 3A range

Temperature Coefficient:

0°C to (Cal. Temp. − 5°C),(Cal. Temp + 5°C) to 55°C
5½ digit display, auto-zero ON
± (% of reading + number of counts)/°C

Range	Temperature Coefficient
300mA	0.012 + 5
3 A	0.012 + 0.5

Maximum Burden at Full Scale:

1V

Maximum Reading Rates:

Same as dc volts

AC CURRENT (true rms responding)

Input Characteristics:

Range	Maximum Reading (5½ Digit)	Resolution 5½ Digit	4½ Digit	3½ Digit
300mA	303.099mA	1µA	10µA	100µA
3 A	3.03099 A	10µA	100µA	1mA

Maximum Input: (non-destructive)

3A from < 250V source fuse protected

Measurement Accuracy:

± (% of reading + number of counts)
Auto zero ON 5½ digit display accuracy specified for sine wave inputs only > 10% of full scale
1 YEAR CAL TEMP ± 5°C

Frequency	Ranges 300mA	3A
20Hz − 50Hz	1.54 + 163	2.24 + 163
50Hz − 1kHz	0.81 + 163	1.5 + 163
1kHz − 10kHz	0.72 + 163	1.42 + 163
10kHz − 20kHz	0.86 + 163	1.56 + 163

Auto zero Off:

5½ digits) for a stable environment (± 1°C), for < 24 hrs add 10 counts to accuracy specification

Temperature Coefficient:

0°C to 55°C
5½ digits, auto-zero ON
± (0.021% of reading + 10 counts)/°C

Maximum Burden at Full Scale:

1V

Crest Factor:

>4:1 at full scale

Maximum Reading Rates:

Same as ac volts

GENERAL INFORMATION

Operating Temperature:

0 to 55°C

Humidity Range:

95% R.H., 0 to 40°C

Storage Temperature:

− 40°C to 75°C

Warm-up Time:

1 hr. to meet all specifications

Integration Time.

Number of Digits	Line Frequency 50Hz	60Hz
5½	200ms	166.7ms
4½	20ms	16.67ms
3½	2ms	1.667ms

Power

AC Line 48 − 440Hz 86 − 250V (see configuration)

Maximum Power

< 25 watts

Size

102mm H × 215mm W × 356mm D
(4 in H × 8 in W × 14 in D)

Weight

3kg (6.5 lbs.)

Figure 16. Technical Specifications for the Hewlett-Packard Model 3478A Multimeter. (continued)

TECHNICAL SPECIFICATIONS FOR THE HEWLETT-PACKARD
MODEL 6825A BIPOLAR POWER SUPPLY/AMPLIFIER

GENERAL SPECIFICATIONS

Input Power:
104-127/208-254Vac (switchable), 48-63Hz, 1.0A, 150W

Meters:
Individual voltage and current meters. DC accuracy is 3% of full scale. AC accuracy is 5% of full scale with sinusoidal, 100Hz input.

Meter Ranges (DC):
±2.4V, ±24V/±0.24A, ±2.4A

Meter Ranges (AC):
1.6V (uncal), 16V rms/0.16A rms, 1.6A rms

Temperature Ratings:
Operating: 0 to 55°C.
Storage: −40 to +75°C.

Cooling:
Convection cooling is employed. The supplies have no moving parts.

Dimensions:
See outline diagram, Figure 2-1.

Weight:
18 lbs. (8.2 kg.) net, 21 lbs. (9.5 kg.) shipping.

POWER SUPPLY SPECIFICATIONS

DC Output:
Voltage and current spans indicate range over which output may be varied.
X1 Range: −5V to +5V, 0 to 2.0A
X4 Range: −20V to +20V, 0 to 2.0A

Load Effect (Load Regulation):
Voltage load effect is given for a load current change equal to the current rating of the supply. Current load effect is given for a load voltage change equal to the voltage rating of the supply.
Voltage (X1 Range): 0.01% + 1mV
Voltage (X4 Range): 0.01% + 5mV
Current: .01% + 250μA

Source Effect (Line Regulation):
For a change in line voltage between 104 and 127Vac/208 and 254Vac at any output voltage and current within rating.

Source Effect (Line Regulation) Continued:
Voltage (X1 Range): .01% + .2mV
Voltage (X4 Range): .01% + 2mV
Current: .01% + 250μA

PARD (Ripple and Noise):
Rms/p-p (20Hz to 20MHz) at any line voltage and under any load condition within rating.
Voltage (X1 Range): 1.5mV rms/4mV p-p
Voltage (X4 Range): 5mV rms/15mV p-p
Current: 3mA rms/10mA p-p

Temperature Coefficient:
Output change per degree Centigrade change in ambient following 30 minutes warm-up.
Voltage (X1 Range): .01% + 35mV
Voltage (X4 Range): .01% + 1.5mV
Current: .02% + 100μA

Drift (Stability):
Change in output (dc to 20Hz) over 8 hour interval under constant line, load, and ambient following 30 minutes warm-up.
Voltage (X1 Range): .03% + 1mV (Pot wiper jump effect may add 5mV)
Voltage (X4 Range): .03% + 5mV (Pot wiper jump effect may add 50mV)
Current: .1% + 200μA (Pot wiper jump effect may add 1.5mA)

Load Effect Transient Recovery (Load Transient Recovery):
Time required for output voltage recovery to within the specified level of the nominal output voltage following a change in output current equal to the current rating of the supply:
100μsec is required for output voltage recovery within 20mV of nominal output voltage.

Resolution:
Typical output voltage or current change that can be obtained using front panel controls.
Voltage (X1 Range): 10mV
Voltage (X4 Range): 40mV
Current: 3mA

Output Impedance (Typical to 50kHz):
Approximated by a resistance in series with an inductance (constant voltage operation).
5mΩ & 1.5μH

Figure 17. Technical Specifications for the Hewlett-Packard Model 6825A Bipolar Power Supply/Amplifier. [Ref. 9: pp. 1.2-1.3]

POWER SUPPLY SPECIFICATIONS (Continued)

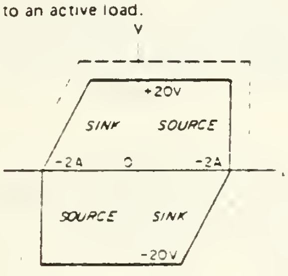
DC Output Isolation:
Supply may be floated at up to 300V above ground.

Remote Resistance Programming:
Resistance Coefficient:
Voltage (X1 Range): 2000Ω/V ± .1%
Voltage (X4 Range): 500Ω/V ± .1%
Current: 5Ω/mA ± .1%

Remote Programming Speed:
50μsec are required to change between 1% and 99% of the maximum + and − voltage limits.

Remote Programming Temperature Coefficient:
Output change per degree Centigrade change in ambient using an external control resistor (R_F) at output voltage (V_O) or current (I_O). % T.C. R_F is the temperature coefficient of the control resistance R_F.
Voltage (X1 Range): .25mV + .007% (V_O) + % T.C. R_F (V_O + 5)
Voltage (X4 Range): 1mV + .007% (V_O) + % T.C. R_F (V_O + 20)
Current: .016% (I_O) + 33μA + % T.C. R_F (I_O)

Sink Current Compliance:
Maximum current that the supply can sink when connected to an active load.



Sink current is limited to a value ranging linearly from 2A @ 0V to 1A @ 20V
Externally applied voltages to output terminals in excess of 25V could damage the instrument.

POWER AMPLIFIER SPECIFICATIONS

Output:
Voltage (X1 Range): 10V p-p
Voltage (X4 Range): 40V p-p
Current: 2A peak

Voltage Gain (High/Low Range):
Fixed Amplifier (Inverting): 4X (high range)/ 1X (low range)
Variable Gain (Non-Inverting): 0-8 (high range)/ 0-2 (low range)

Frequency Response (+1, −3dB at full output):
Fixed Gain: dc − 40kHz
Variable Gain: dc − 15kHz

Distortion:
Total harmonic distortion is .1% (maximum) at 100Hz and full output.

Input Impedance:
10KΩ (Typical)

Fixed Gain Accuracy (at 100Hz):
Low Range (X1): 1% + 5mV
High Range (X4): .1% + 2mV

Remote Resistance Programming Variable Gain (A_V):

$$A_V = \frac{KR_F}{10.24 \times 10^3 \Omega}$$, where K is the constant indicated and R_F is the external control resistance.

$$A_V \text{ at low range (X1): } \frac{R_F}{10.24 \times 10^3}$$

$$A_V \text{ at high range (X4): } \frac{4R_F}{10.24 \times 10^3}$$

Variable Gain Accuracy:
Accuracy in high range at 100Hz using an external control resistance (R_F) at output voltage (V_O). % R_F is the accuracy of the control resistance R_F:
(1.05% + % R_F) V_O + 2.5mV

Remote Voltage Control Coefficient:
Fixed gain amplifier mode voltage coefficient:
Voltage (X1 Range): 1 volt/volt ± 1%
Voltage (X4 Range): 4 volts/volt ± 1%

Variable gain amplifier mode (VOLTAGE control fully clockwise), voltage coefficient:
Voltage (X1 Range): 2 volts/volt ± 1%
Voltage (X4 Range): 3 volts/volt ± .1%

Constant Current, voltage coefficient (the following applies to variable gain amplifier, fixed gain amplifier, and power supply modes of operation):
2 amperes/volt ± 5%

Figure 17. Technical Specifications for the Hewlett-Packard Model 6825A Bipolar Power Supply/Amplifier. (continued)

TECHNICAL SPECIFICATIONS FOR THE HEWLETT-PACKARD
MODEL 59501B ISOLATED DAC/POWER SUPPLY PROGRAMMER

D/A CONVERTER

DC Output Voltage: Programmable in high or low ranges within the voltage limits shown below. Output mode is unipolar or bipolar and is selectable via rear panel switch.

	High	Low
Unipolar	0 to 9.99 Volts	0 to +.999 Volts
Bipolar	−10 to +9.98 Volts	−1 to +.998 Volts

DC Output Current: 10mA

Resolution:

	High	Low
Unipolar	10mV	1mV
Bipolar	20mV	2mV

Accuracy: Specified at 23° C ± 5°C

	High	Low
Unipolar	.1% + 5mV	.1% + 1mV
Bipolar	.1% + 10mV	.1% + 2mV

* **Stability:** Change in output over 8 hour interval under constant line, load, and ambient following a 30 minute warm-up.

	High	Low
Unipolar	.04% + 5mV	.04% + .1mV
Bipolar	.04% + 1mV	.04% + .2mV

Temperature Coefficient:

	High	Low
Unipolar	.01%/°C + .5mV/°C	.01%/°C + 1mV/°C
Bipolar	.01%/°C + .5mV/°C	.01%/°C + 1mV/°C

Zero Adjust: Plus or minus 250 millivolts.

D/A Full Scale Adjust: Plus or minus 5%.

Programming Speed: The time required for output to go from zero to 99% of programmed output change is 250μsec (measured with resistive load connected to output terminals)

* Stability is included in accuracy specification measurements over the temperature range indicated

POWER SUPPLY PROGRAMMING

Programming Network Specifications: In the following specifications, M represents the calibrated full scale value of the supply being programmed and P represents the actual programmed output. Note that the full scale value (M) can be any value within the supply's output range and is calibrated with the 59501B programmed to its maximum high range output.

Accuracy (Does not include power supply errors):
Specified at 23°C ± 5°C.

	High	Low
Unipolar	.05%M + .25%P	.01%M + .25%P
Bipolar	0.1%M + .25%P	.02%M + .25%P

Isolation: 600Vdc between HP-IB data lines and output terminals.

Temperature Coefficient:

High	.005%M/°C + .015%P/°C
Low	.01%M/°C + .015%P/°C

Programming Resolution:

	High	Low
Unipolar	0.1%M	0.01%M
Bipolar	0.2%M	0.02%M

Programming Speed: D/A Conversion Time plus the programming speed of the power supply

GENERAL

Input Power: Unit has ac power module which is settable to 100/120/220/240 Vac (−13%, +6%) 48-63Hz, 10VA. A 3-wire detachable line cord is supplied

Temperature Range:
Operating: 0 to 55°C
Storage: −40 to 75°C

Dimensions:
(See Figure 2-1)

Weight:
Net: 1.82 kg (4 lb.)
Shipping: 2.27 kg. (5 lb.)

Figure 18. Technical Specifications for the Hewlett-Packard Model 59501B Isolated DAC/Power Supply Programmer. [Ref. 10: pp. 1-3]

TECHNICAL SPECIFICATIONS FOR THE IBM DATA ACQUISITION ADAPTER (ANALOG INPUT DEVICE)

Analog Input Device

The analog input device has the following characteristics:

Resolution	12 bits
Input Channels	4 differential
Input Ranges	Switch-selectable ranges: 0 to +10 volts (unipolar), -5 to +5 volts (bipolar), and -10 to +10 volts (bipolar).
Input Resistance	100 megohms minimum
Input Capacitance	200 picofarads maximum; measured at the distribution panel connector
Input Leakage Current	±300 nanoamperes maximum
Input Current	±4 milliamperes at maximum input voltage
Digital Coding	Unipolar: binary. Bipolar: offset binary.
Safe Input Voltage	±30 volts maximum (power On or Off)
Power Supply Rejection	±1/2 LSB maximum change full scale calibration
Integral Linearity Error	±1 LSB maximum

Figure 19. Technical Specifications for the IBM Data Acquisition Adapter (Analog Input Device). [Ref. 11: pp. 116-118]

Differential Linearity Error	±1/2 LSB maximum
Differential Linearity Stability	±5 ppm/°C maximum; guaranteed monotonic
Gain Error	±0.1% maximum between ranges. Any range adjustable to zero.
Gain Stability	±32 ppm/°C of FSR maximum
Common-Mode Input Range	±11 volts maximum
Common-Mode Rejection	72 dB minimum ratio (signal within common-mode range)
Unipolar Offset Error	Adjustable to zero
Unipolar Offset Stability	±24 ppm/°C of FSR maximum
Bipolar Offset Error	Adjustable to zero
Bipolar Offset Stability	±24 ppm/°C of FSR maximum

Figure 19. Technical Specifications for the IBM Data Acquisition Adapter (Analog Input Device). (continued)

Settling Time	For channel acquisition: 20 microseconds maximum to ±0.1% of the input value
Conversion Time	35 microseconds maximum
Throughput to Memory	15,000 conversions per second, minimum
'A/D convert enable'	
Input Impedance	One LS TTL load plus 10-kilohm pull-up resistor
'A/D convert out'	
Fanout	10 LS TTL loads or 2 standard TTL loads

Figure 19. Technical Specifications for the IBM Data Acquisition Adapter (Analog Input Device). (continued)

APPENDIX B

OPERATIONAL AND CALIBRATION PROCEDURES

This appendix contains specific detailed instructions for operation and calibration of the solar simulator laboratory and the automated solar cell test program. The operational procedures are written in a step-by-step format. Since the use of the Kratos light source requires caution, it is recommended that they be followed in order.

A. OPERATIONAL PROCEDURES

1. One hour prior to test-

(a) Turn on temperature control circulator and select desired test temperature.

(b) Turn on circulator pump housing vent fan.

(c) Turn on Omega digital temperature display.

2. One half hour prior to test-

(a) Turn on water circulating pump for the IR filter.

(b) Turn on upper and lower lamp housing vent fans.

(c) Start Kratos light source power supply.

(d) Disconnect DAC adapter. This step is recommended due to the possibility of damage to the DAC adapter card by the 40 KV R.F. pulse needed to start the Kratos lamp.

(e) Plug in Kratos lamp starter unit.

(f) Put on safety goggles (filters ultraviolet radiation to protect the eyes).

(g) Activate the toggle switch on the starter unit to the `start´ position. Hold for no longer than 10 sec. The switch is a momentary contact type and will spring release. The lamp should start immediately, however if it is hot, a cool down period is required prior to restart. If difficulties are encountered consult the Kratos literature.

(h) Disconnect the Kratos lamp starter unit.

(i) Turn on HP 59501B power supply programmer.

(j) Turn on HP 6825A bipolar power supply.

(k) Turn on HP 3478A digital multimeter.

3. Fifteen minutes prior to test-

(a) Turn "cool-on" switch on temperature control circulator to on position.

(b) Turn on IBM PC/XT and HP 7475 plotter.

(c) Plug in DAC adapter connection cable. Arrow points upward.

4. Test time-

(a) Start vacuum pump.

(b) Place test/setup switch on test module to "setup" position.

(c) Using a secondary standard, verify Air Mass Zero solar intensity, by comparing the secondary standard output voltage to that voltage supplied with the standard

cell documentation. Adjust lamp current or cell position as necessary to achieve proper voltage.

(d) Place solar cell on test block using plastic tweezers.

(e) Start test program by typing "BASICA CORPROG" to the right of the cursor C>, and then follow the user friendly directions.

(f) When running the calibration routine the Eppley standard cell voltage should be 1.0188 +/- .0002 volts.

5. Post test-

(a) Secure the Kratos lamp power supply.

(b) Secure the vacuum pump.

(c) Secure the temperature control circulator pump.

(d) Turn off the HP 6825A power supply, HP 59501B power supply programmer, computer, and plotter.

(e) Leave all vent fans and the IR filter water circulator running for at least one (1) hour following Kratos shutdown.

B. Calibration Procedures

1. Discussion

Two areas of the test system require periodic calibration. These are: the A/D channels used for voltage measurements and the programmable power supply output.

2. Analog to Digital Converter Calibration

As discussed in Chapter III, selecting menu routine number 1 in the test program calculates the voltage

offsets required for calibration of the two analog to digital converter channels. Since the two offsets calculated are used throughout the cell test routine, this routine must be run prior to commencement of a test session. The calibration of menu routine number 1 needs to be run only once upon entering the program, however, since the values of the offsets are stored in the variables C1 and C2. Therefore, the calibration of the A/D card is assured each time the routine is run.

3. Power Supply Programming

Programming of the power supply to a given output is accomplished by calculating a specific digital code and transmitting this code over the IEEE 488 GPIB bus to the HP 59501B/6825A power supply combination which outputs the appropriate analog voltage. For this application the code is a number between 1000 and 1999. The total number of programming steps available for use is 999. A code of 1999 corresponds to a maximum output and a code of 1000 corresponds to a minimum output. The resolution of the power supply may then be determined by dividing the total voltage swing by the total number of programming steps. Algebraically,

$$[V_{max} + V_{min}] / 999 = \text{resolution (volts/step)} \quad (9)$$

For this application the maximum open circuit voltage for any one gallium arsenide cell used was 1.001 volts. Thus V_{max} was initially chosen to be 1.010 volts. The power supply literature states that the minimum resolution possible is 1.5 millivolts/step which yields a V_{min} of -0.4885 volts (1.01 - 999 x 0.0015). Adjustments were made to the power supply to yield a V_{max} of 1.0098 volts and a V_{min} of -0.4629 volts and a resolution of

$$[1.0098 + 0.4629] / 999 = 1.47 \text{ mV/step} \qquad (10)$$

which is greater than the specifications would suggest. For these values of V_{max} and V_{min}, a zero voltage output was achieved with a code of 1314.

Any desired voltage may then be coded by the relation:

$$\text{code} = [\text{Voltage desired}] / [V_{max} + V_{min}] \times 999 + \text{zero offset} \qquad (11)$$

or

$$\text{code} = V_{des} / 1.4727 \times 999 + 1314 \qquad (12)$$

or

$$\text{code} = V_{des} \times 678.346 + 1314 \qquad (13)$$

where 678.346 is the constant multiplier (c.m.). (See line 3280 of the program in Appendix B).

a. Power Supply Calibration Procedures

Power supply calibration is required when the voltage programmed is not equal to the voltage output. This condition is evidenced by the output voltage failing to be within 1.5 mV of the cell V_{OC}. A statement to this effect is displayed to the user by line number 3500 in the cell test subroutine. The following steps detail the calibration procedure required:

(1) Connect the power supply outputs to a digital voltmeter with a minimum resolution of 10 microvolts

(2) Enter the GPIB sub-directory on the IBM PC/XT.

(3) Type IBIC [return] at the C> prompt (this initiates a GPIB program that allows keyboard input to a GPIB programmable device).

(4) Type IBFIND psupp [return] at the IBIC> prompt.

(5) Type IBWRT "1999" at the psupp: prompt. This drives the power supply to maximum output. The voltage should be 1.0098 volts (+/- 100 microvolts). Record the voltage.

(6) Type IBWRT "1000". This drives the power supply to -0.4629 volts (+/- 100 microvolts). Record the voltage.

(7) Type IBWRT "1314". The output should now be -0.03 millivolts (+/- 10 microvolts). Record the voltage.

(8) If the above specifications are not met, then the HP 59501B power supply full scale adjust and zero adjust potentiometers must be adjusted to regain the required precision. This procedure entails frequent use of the IBWRT command and may require a significant amount of time.

(9) Upon completion of steps (5) - (7), recalculate the constant multiplier (c.m.) in equation (13), or

$$c.m. = 999 / [V_{max} + V_{min}]$$

(10) Insert this value in line 3280 of the test program.

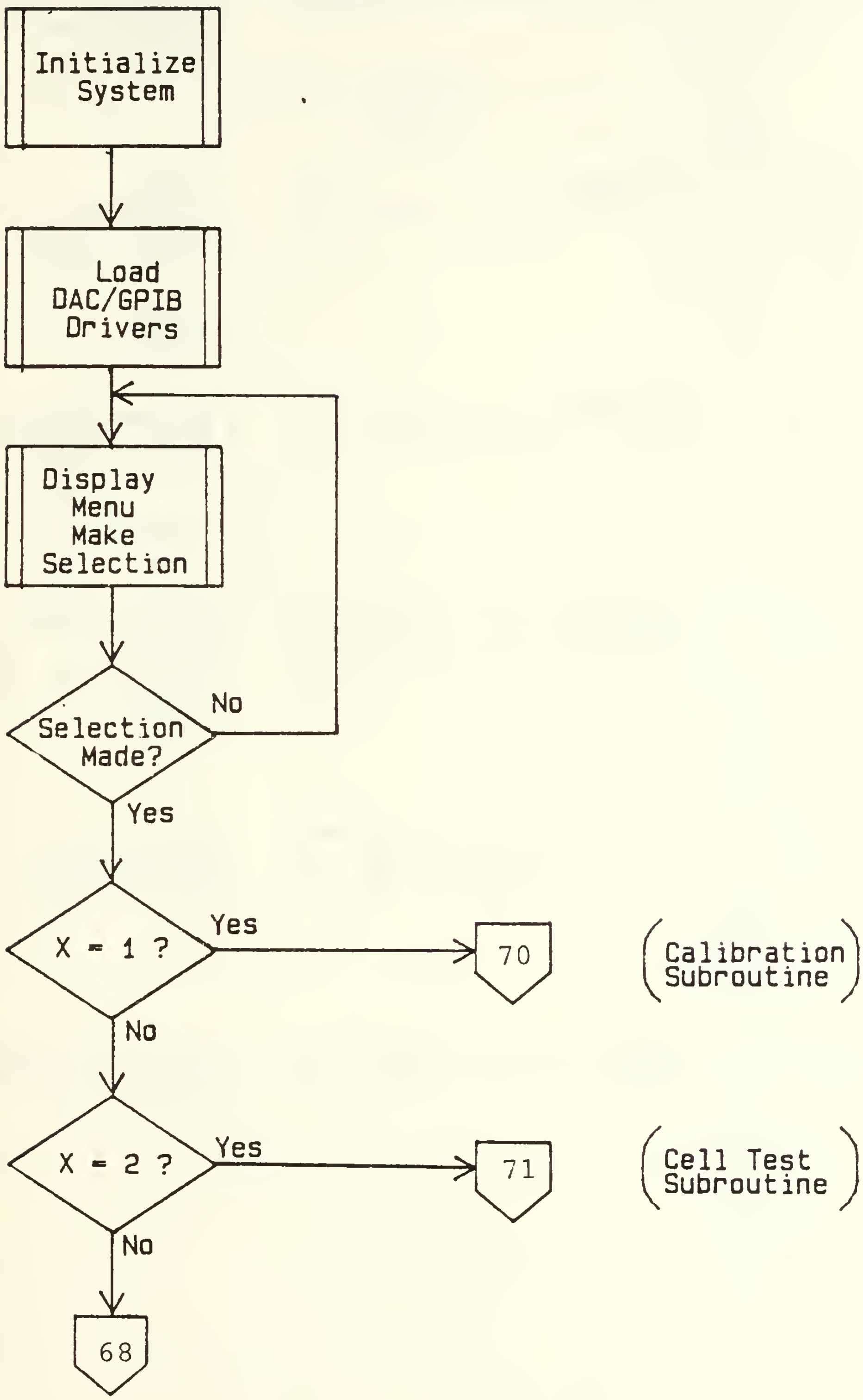
(11) Calculate 70 % of the c.m. and insert this value in line 3290.

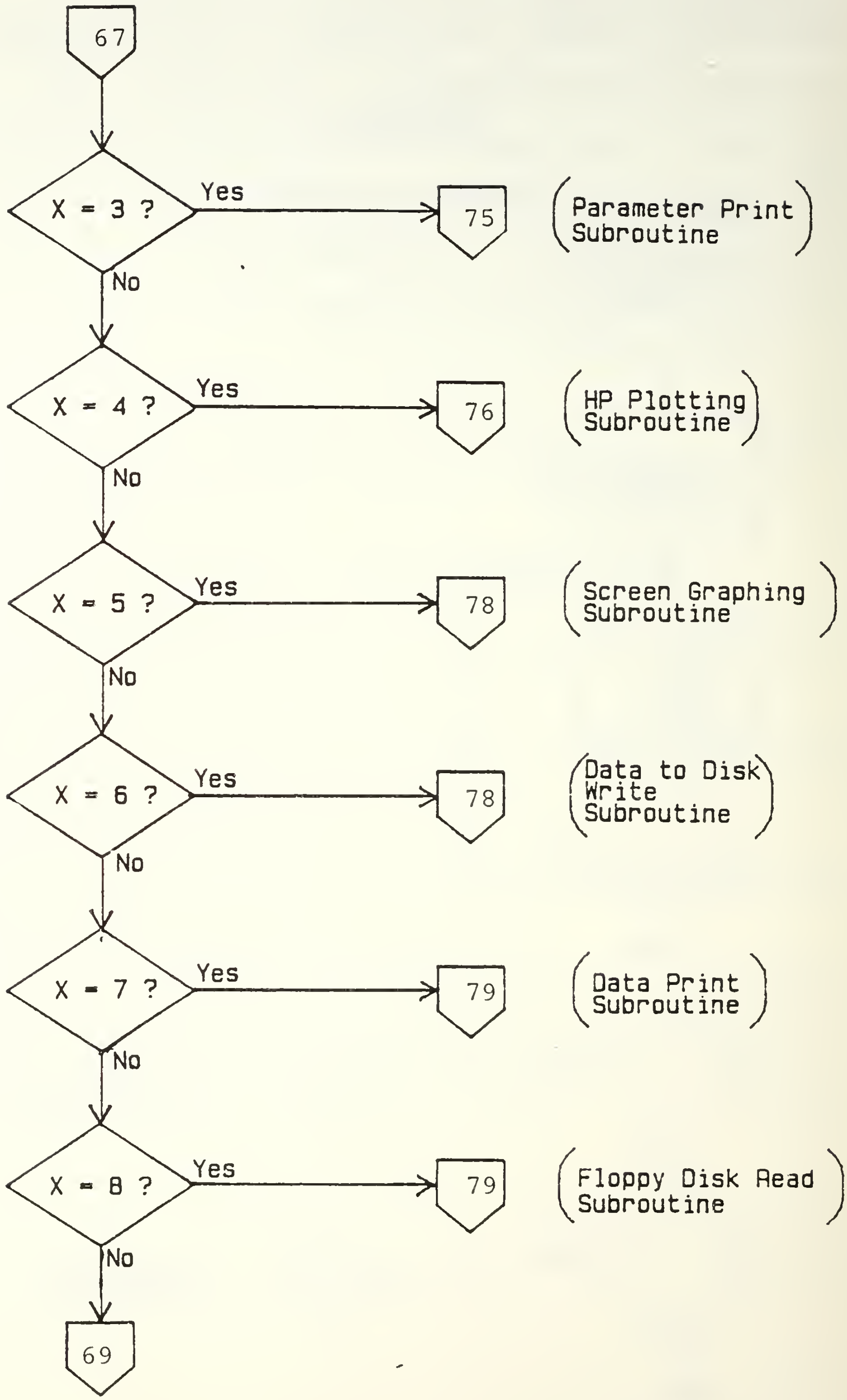
(12) Calculate 3 % of the c.m. and insert this value in line 3300.

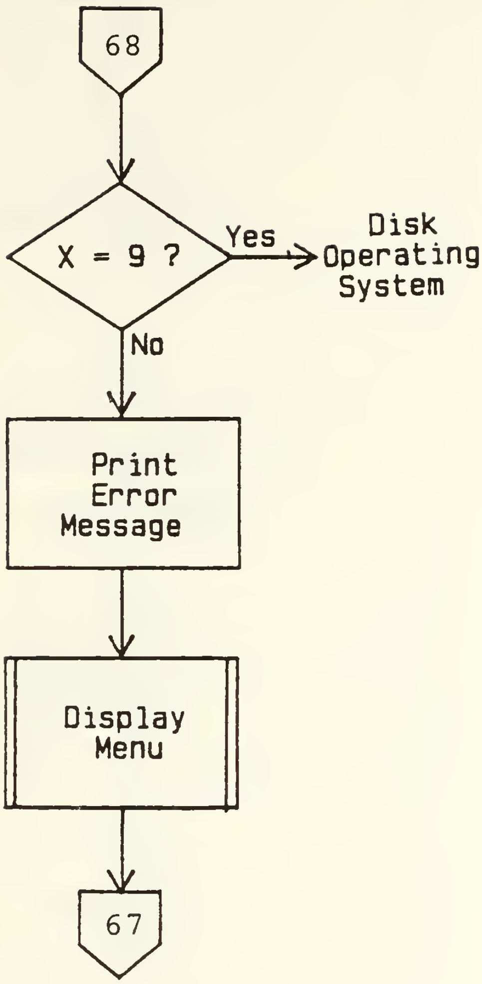
b. It should be noted that the HP 59501B/6825A combination is exceptionally stable after a 30 minute warm-up period, and this calibration procedure is not often required.

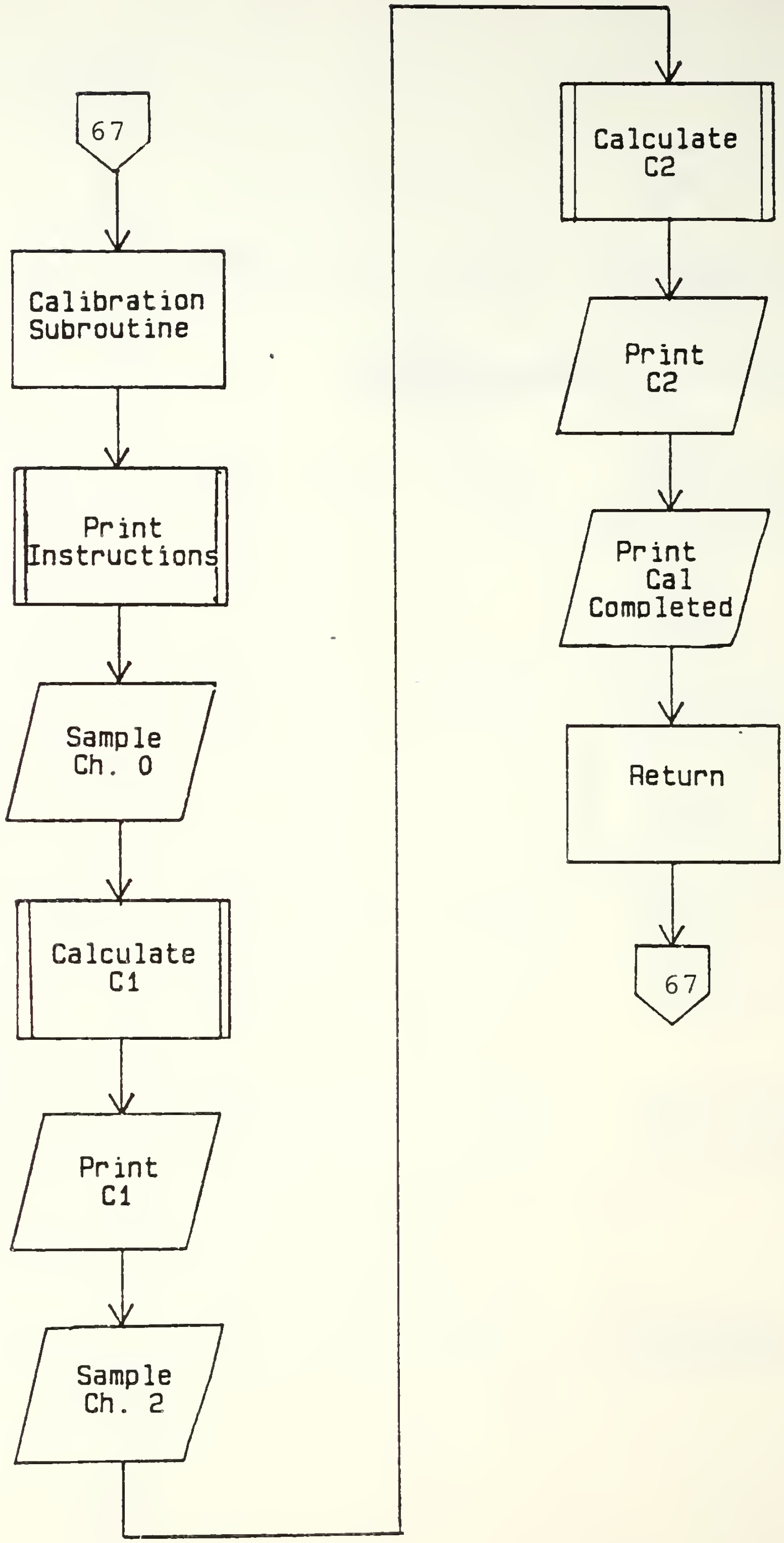
APPENDIX C

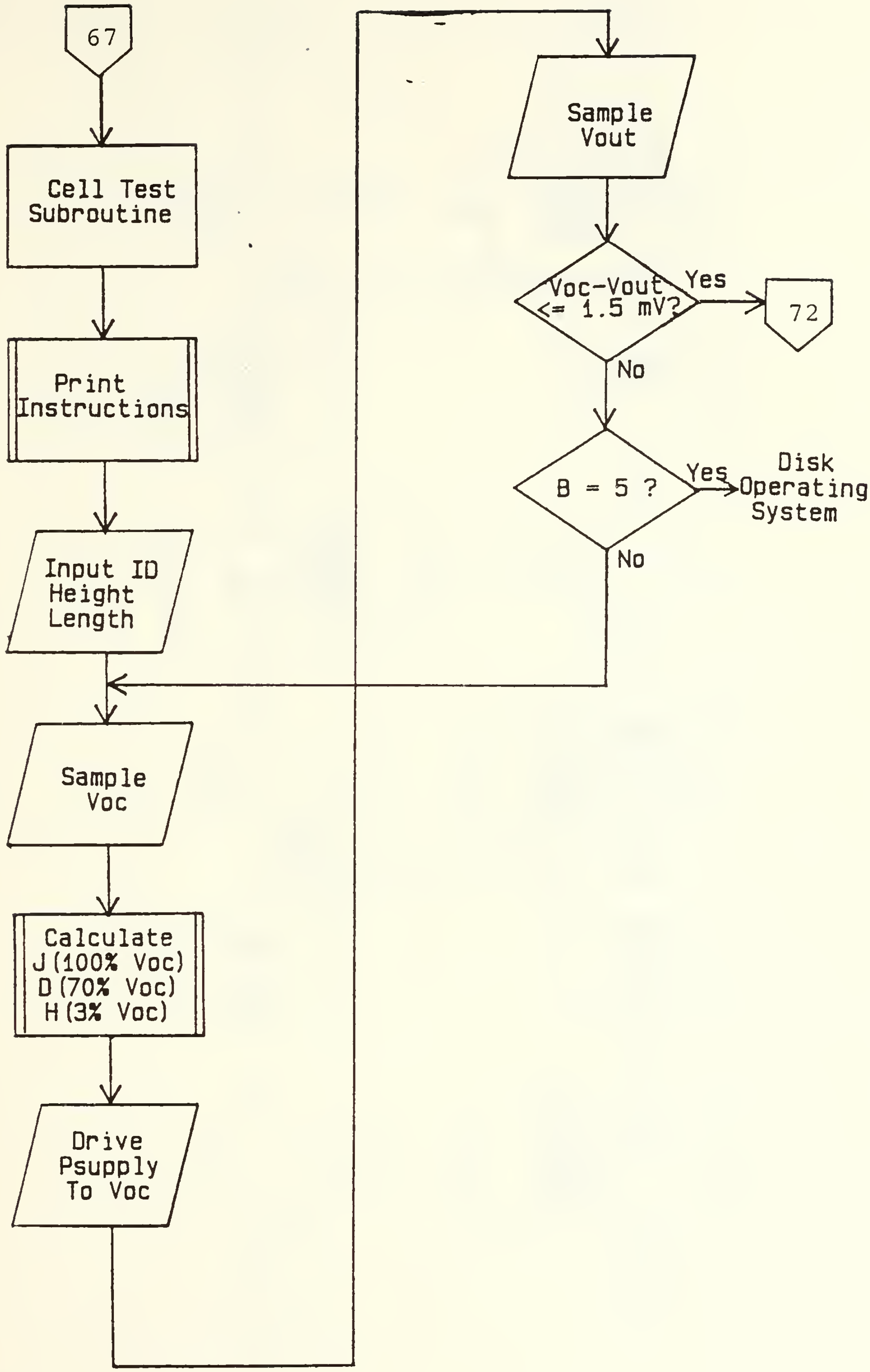
SOFTWARE FLOWCHART

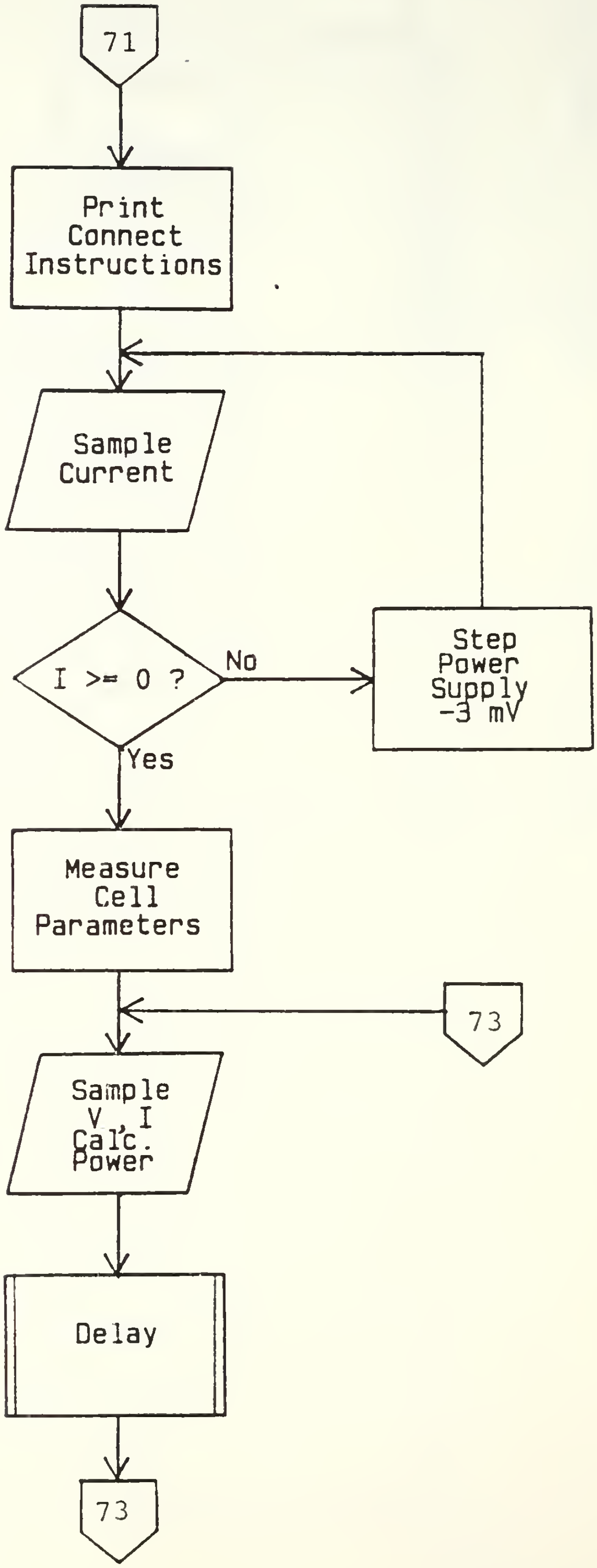


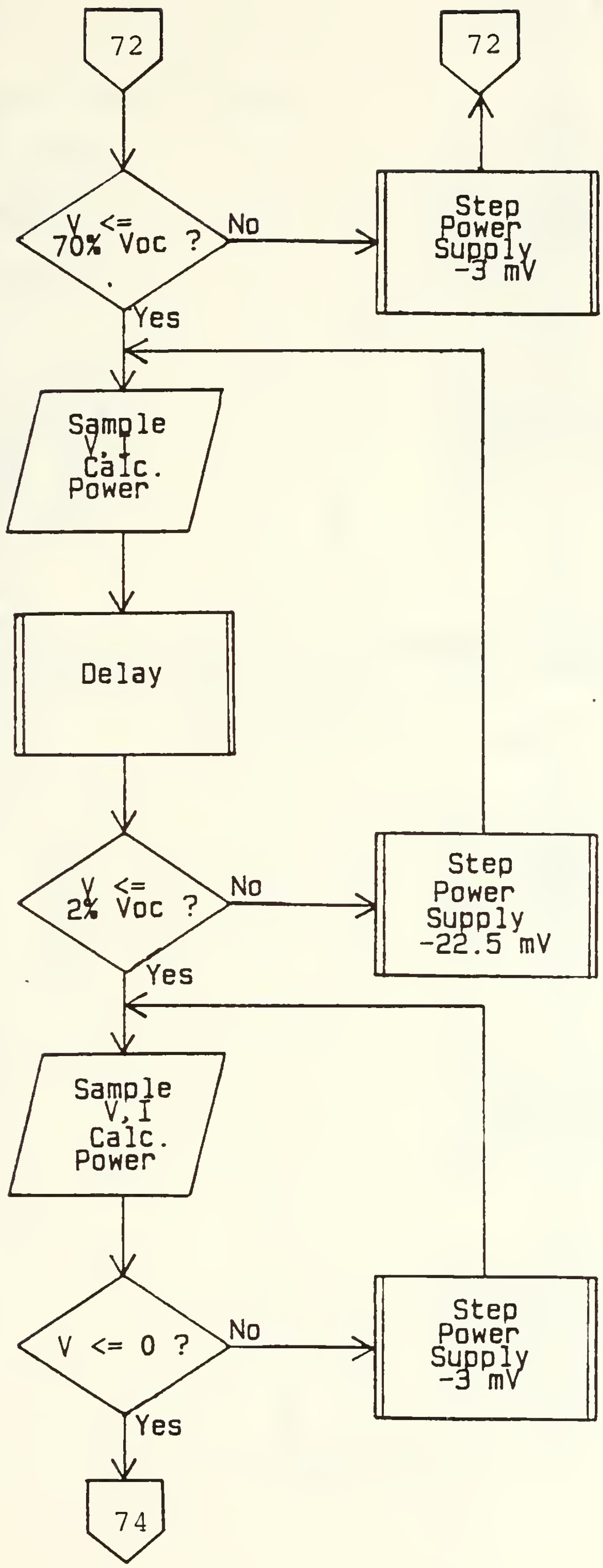

67
X = 3 ?
Yes
75
Parameter Print Subroutine
No
X = 4 ?
Yes
76
HP Plotting Subroutine
No
X = 5 ?
Yes
78
Screen Graphing Subroutine
No
X = 6 ?
Yes
78
Data to Disk Write Subroutine
No
X = 7 ?
Yes
79
Data Print Subroutine
No
X = 8 ?
Yes
79
Floppy Disk Read Subroutine
No
69

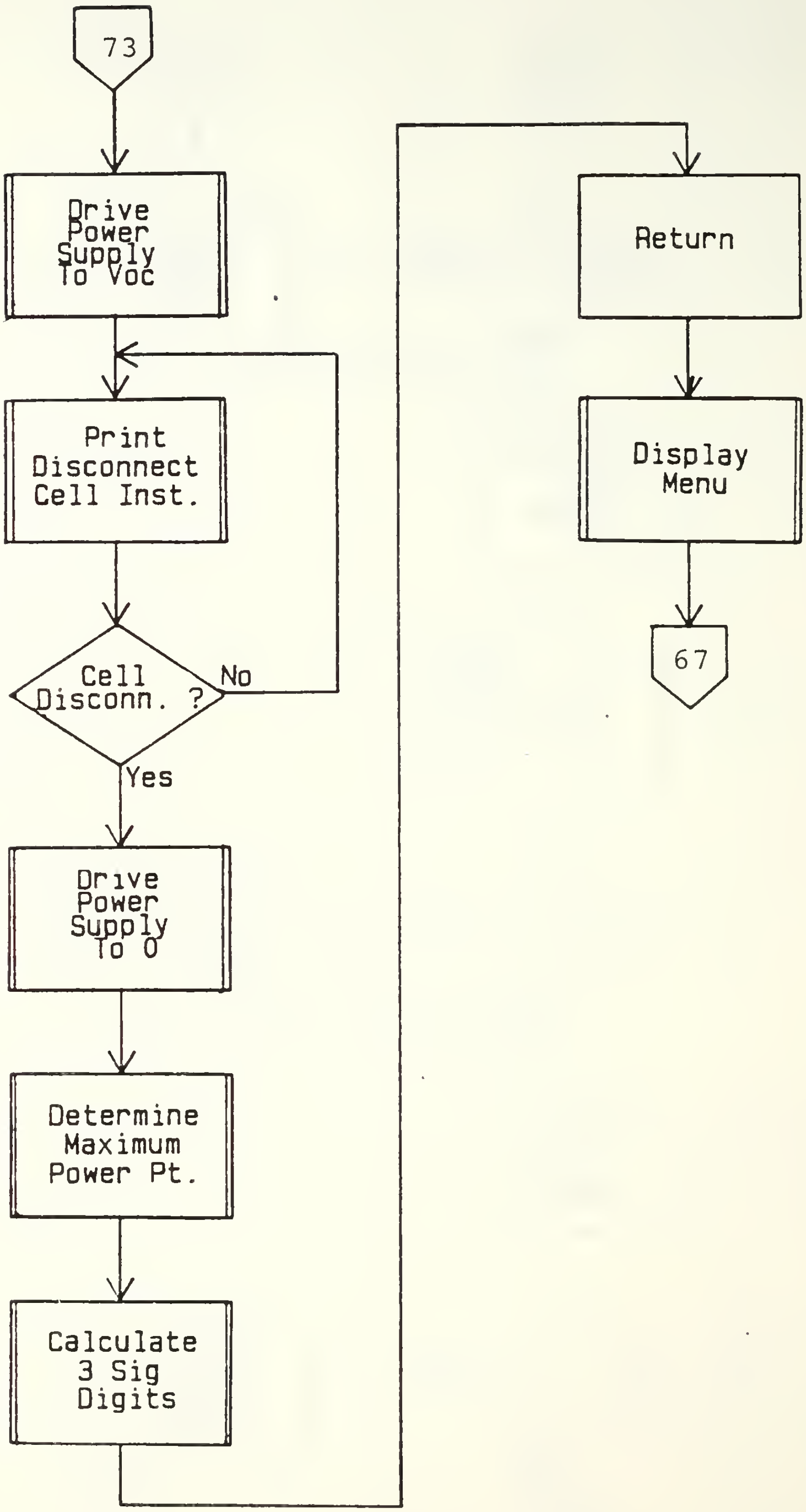

68
X = 9 ?
Yes
Disk Operating System
No
Print Error Message
Display Menu
67

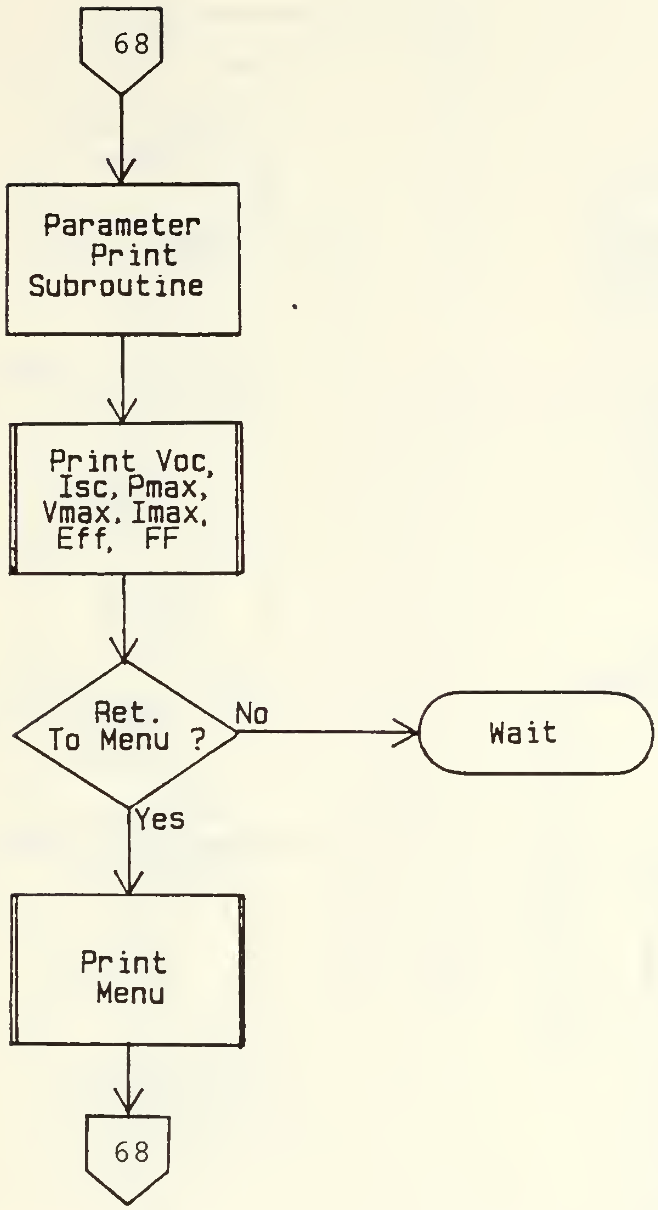

67
Calibration Subroutine
Print Instructions
Sample Ch. 0
Calculate C1
Print C1
Sample Ch. 2
Calculate C2
Print C2
Print Cal Completed
Return
67

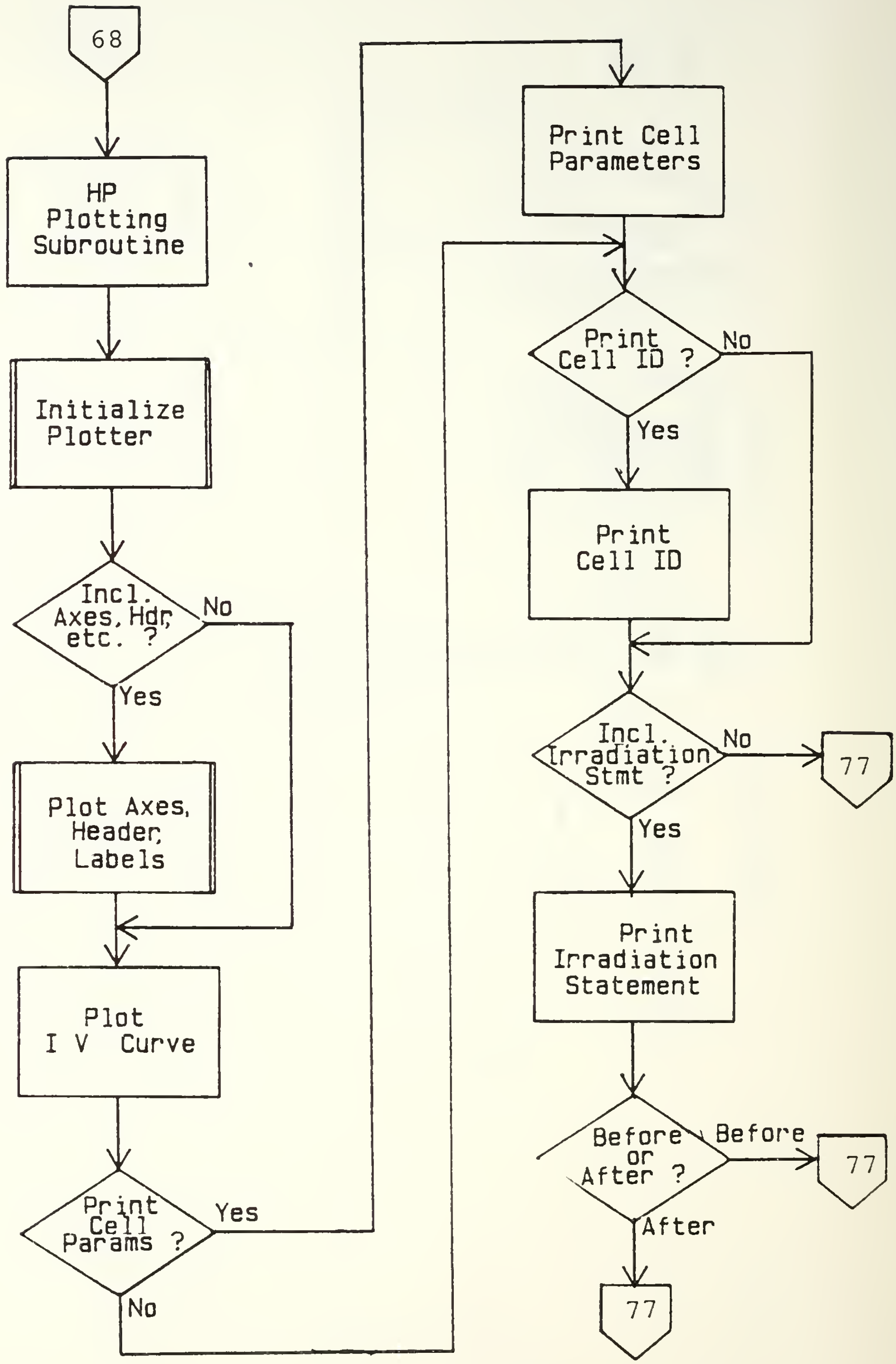

67
Cell Test Subroutine
Print Instructions
Input ID Height Length
Sample Voc
Calculate J (100% Voc) D (70% Voc) H (3% Voc)
Drive Psupply To Voc
Sample Vout
Voc-Vout <= 1.5 mV?
Yes
72
No
B = 5 ?
Yes
Disk Operating System
No

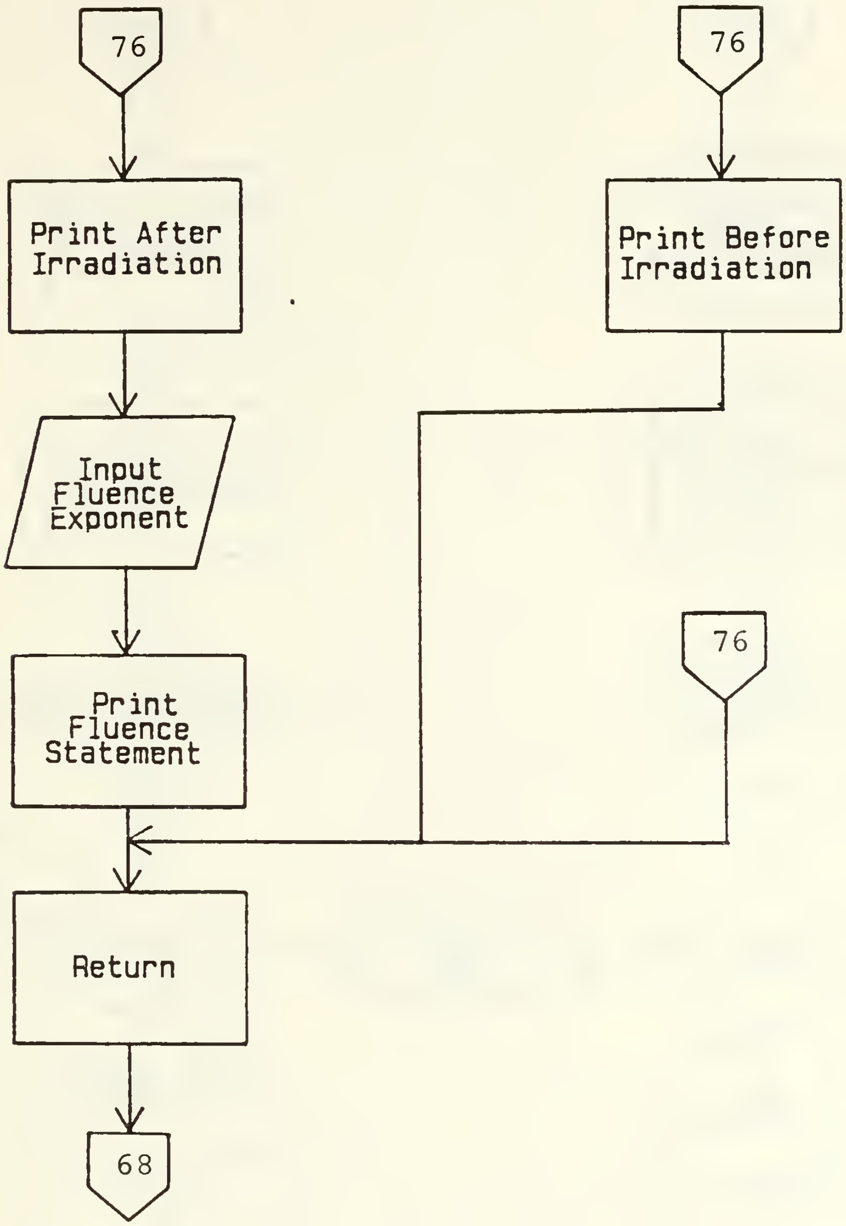

71
Print Connect Instructions
Sample Current
I >= 0 ?
No
Yes
Step Power Supply -3 mV
Measure Cell Parameters
73
Sample V , I Calc. Power
Delay
73

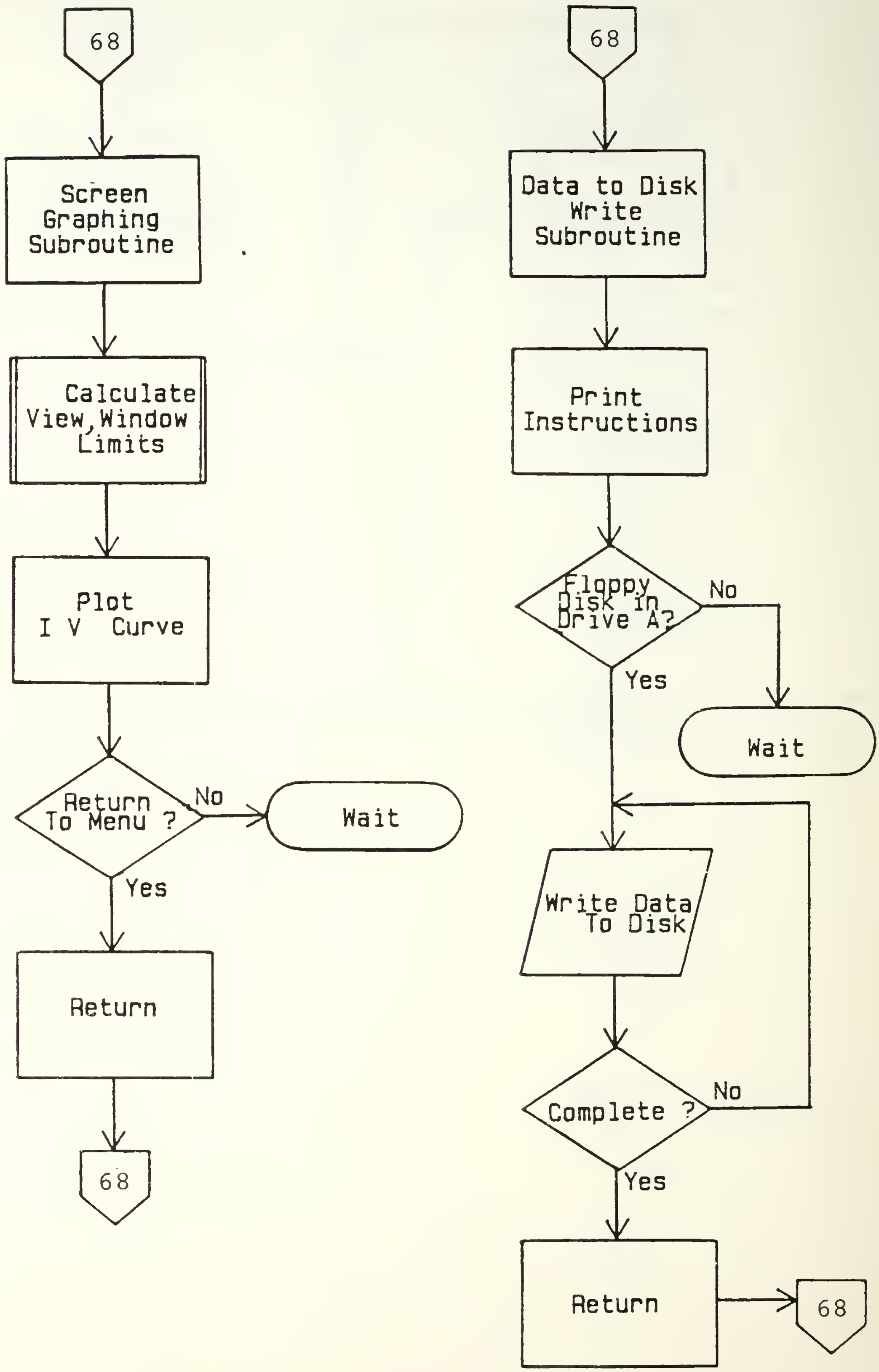

72
72
V <=
70% Voc ?
No
Step
Power
Supply
-3 mV
Yes
Sample
V, I
Calc.
Power
Delay
V <=
2% Voc ?
No
Step
Power
Supply
-22.5 mV
Yes
Sample
V, I
Calc.
Power
V <= 0 ?
No
Step
Power
Supply
-3 mV
Yes
74

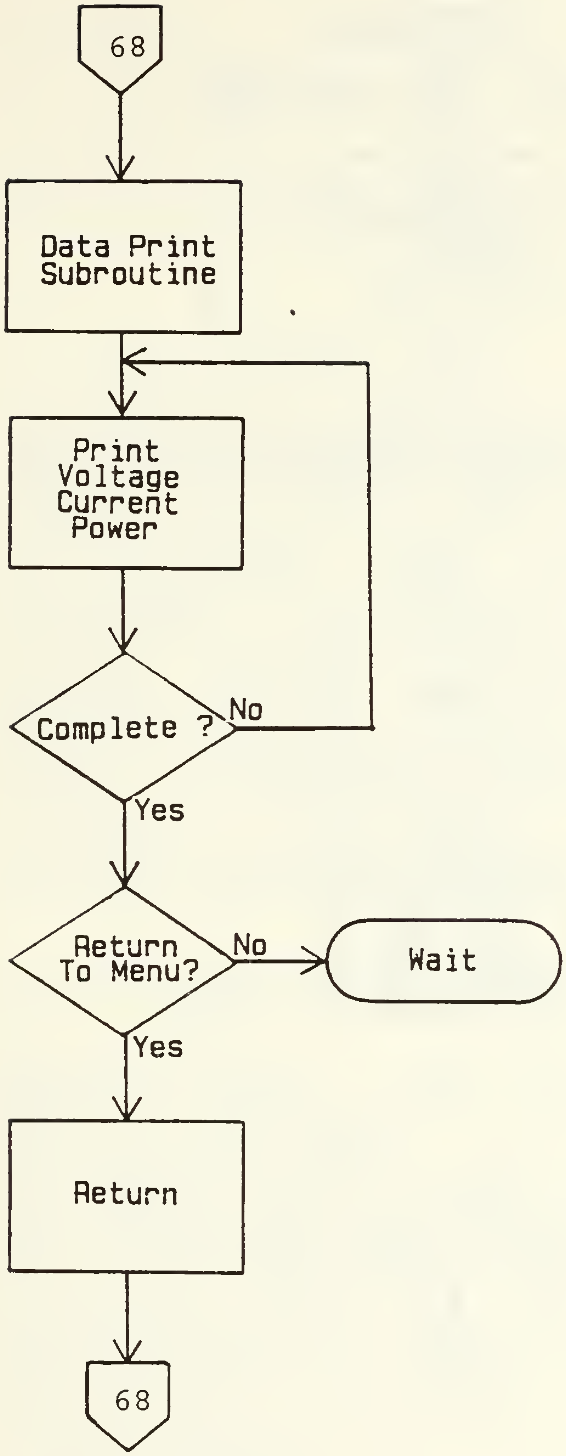

73
Drive Power Supply To Voc
Print Disconnect Cell Inst.
Cell Disconn. ?
No
Yes
Drive Power Supply To 0
Determine Maximum Power Pt.
Calculate 3 Sig Digits
Return
Display Menu
67

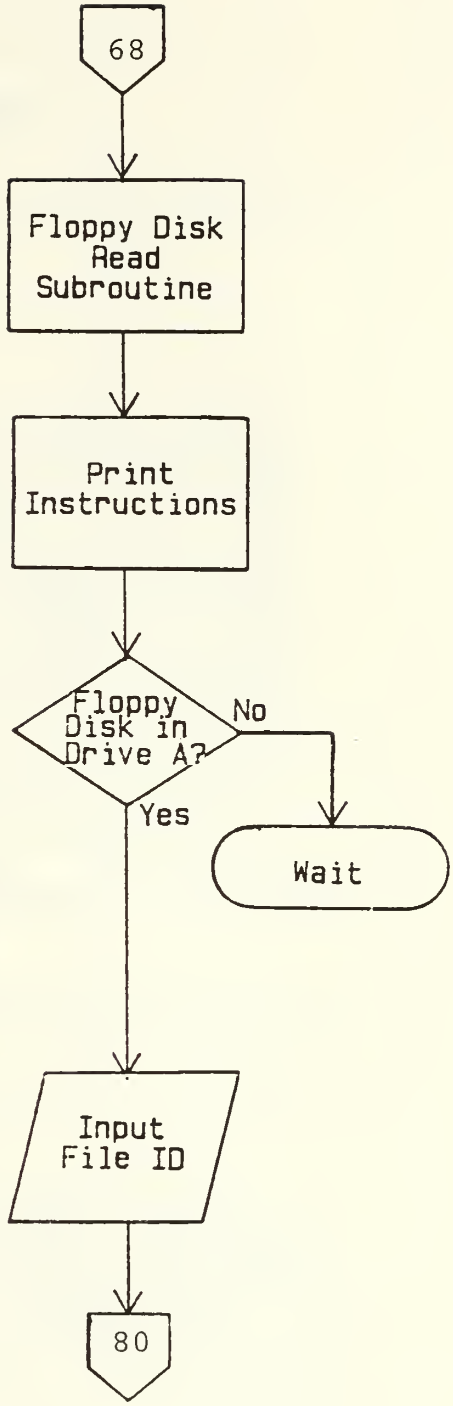

68
Parameter Print Subroutine
Print Voc, Isc, Pmax, Vmax, Imax, Eff, FF
Ret. To Menu ?
No
Wait
Yes
Print Menu
68

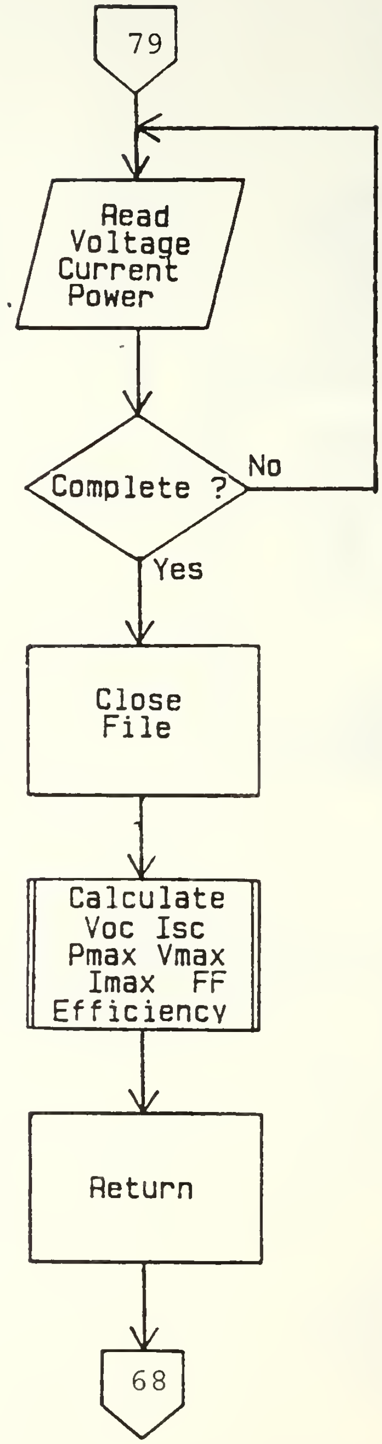

68
HP Plotting Subroutine
Initialize Plotter
Incl. Axes, Hdr, etc. ?
No
Yes
Plot Axes, Header, Labels
Plot I V Curve
Print Cell Params ?
Yes
No
Print Cell Parameters
Print Cell ID ?
No
Yes
Print Cell ID
Incl. Irradiation Stmt ?
No
77
Yes
Print Irradiation Statement
Before or After ?
Before
77
After
77


76
Print After Irradiation
Input Fluence Exponent
Print Fluence Statement
Return
68
76
Print Before Irradiation
76


68
Screen Graphing Subroutine
Calculate View, Window Limits
Plot I V Curve
Return To Menu ?
No
Wait
Yes
Return
68
68
Data to Disk Write Subroutine
Print Instructions
Floppy Disk in Drive A?
No
Yes
Wait
Write Data To Disk
Complete ?
No
Yes
Return
68


68
Data Print
Subroutine
Print
Voltage
Current
Power
Complete ?
No
Yes
Return
To Menu?
No
Wait
Yes
Return
68


68
Floppy Disk
Read
Subroutine
Print
Instructions
Floppy
Disk in
Drive A?
No
Wait
Yes
Input
File ID
80


79
Read
Voltage
Current
Power
Complete ?
No
Yes
Close
File
Calculate
Voc Isc
Pmax Vmax
Imax FF
Efficiency
Return
68

APPENDIX D

SOLAR CELL TEST PROGRAM

```
100 '   **************************************************
110 '   *                 CORPROG.BAS                    *
120 '   *                                                *
130 '   *                     BY                         *
140 '   *                                                *
160 '   *                 DON W. GOLD                    *
180 '   * ---------------------------------------------- *
190 '   * THIS PROGRAM WAS WRITTEN TO PROVIDE AN AUTO-   *
200 '   * MATIC METHOD FOR DETERMINING SOLAR CELL PARA-  *
210 '   * METERS.  IT IS MENU  DRIVEN AND  REQUIRES THE  *
220 '   * USER TO PROVIDE AN IBM DATA ACQUISITION CARD,  *
230 '   * A  GPIB INTERFACE  CARD, AN  IEEE-488 CAPABLE  *
240 '   * MULTIMETER, AND  AN IEEE-488  CAPABLE BIPOLAR  *
250 '   * POWER SUPPLY. THE GRAPHICS  PORTION  OF  THE   *
260 '   * PROGRAM  IS WRITTEN  FOR  AN HP 7475A PLOTTER  *
270 '   * AND THE CONNECTION DIAGRAM FOR THE SYSTEM MAY  *
280 '   * MAY BE FOUND IN CH 2, FIGURE (3). THE  GPIB    *
290 '   * DRIVER IS REPRODUCED FROM REF 12 AND THE DAC   *
300 '   * DRIVER IS  REPRODUCED  FROM REF 13.   THEIR    *
310 '   * INCLUSION  IN  THE PROGRAM  IS  REQUIRED TO    *
320 '   * OPERATE THE RESPECTIVE DEVICE.                 *
330 '   **************************************************
340 '
350 '
360 '   *********START OF GPIB DRIVER*********************
370 '
380      CLEAR   ,59309!           ' IBM BASICA Declarations
390      IBINIT1 = 59309!
400      IBINIT2 = IBINIT1 + 3
410      BLOAD "bib.m",IBINIT1
420      CALL IBINIT1(IBFIND,IBTRG,IBCLR,IBPCT,IBSIC,
         IBLOC,IBPPC,IBBNA,IBONL,IBRSC,IBSRE,IBRSV,IBPAD,
         IBSAD,IBIST,IBDMA,IBEOS,IBTMO,IBEOT,IBRDF,IBWRTF)
430      CALL IBINIT2(IBGTS,IBCAC,IBWAIT,IBPOKE,IBWRT,
         IBWRTA,IBCMD,IBCMDA,IBRD,IBRDA,IBSTOP,IBRPP,IBRSP,
         IBDIAG,IBXTRC,IBRDI,IBWRTI,IBRDIA,IBWRTIA,IBSTA%,
         IBERR%,IBCNT%)
440      REM Optionally include the following declarations
         in your program.
450      REM They provide appropriate mnemonics by which
460      REM  to  reference  commonly  used values. Some
         mnemonics (GET%, ERR%, END%, ATN%) are preceded
470      by "B" in order to distinguish them from BASICA
480      REM keywords.
490      REM
```

```
500     REM GPIB Commands
510     UNL% = &H3F        ' GPIB unlisten command
520     UNT% = &H5F        ' GPIB untalk command
530     GTL% = &H1         ' GPIB go to local
540     SDC% = &H4         ' GPIB selected device clear
550     PPC% = &H5         ' GPIB parallel poll configure
560     BGET% = &H8        ' GPIB group execute trigger
570     TCT% = &H9         ' GPIB take control
580     LLO% = &H11        ' GPIB local lock out
590     DCL% = &H14        ' GPIB device clear
600     PPU% = &H15        ' GPIB ppoll unconfigure
610     SPE% = &H18        ' GPIB serial poll enable
620     SPD% = &H19        ' GPIB serial poll disable
630     PPE% = &H60        ' GPIB parallel poll enable
640     PPD% = &H70        ' GPIB parallel poll disable
650     REM
660     REM GPIB status bit vector
670     REM global variable IBSTA% and wait mask
680     BERR% = &H8000     ' Error detected
690     TIMO% = &H4000     ' Timeout
700     BEND% = &H2000     ' EOI or EOS detected
710     SRQI% = &H1000     ' SRQ detected by CIC
720     RQS% = &H800       ' Device needs service
730     CMPL% = &H100      ' I/O completed
740     LOK% = &H80        ' Local lockout state
750     REM% = &H40        ' Remote state
760     CIC% = &H20        ' Controller-In-Charge
770     BATN% = &H10       ' Attention asserted
780     TACS% = &H8        ' Talker active
790     LACS% = &H4        ' Listener active
800     DTAS% = &H2        ' Device trigger state
810     DCAS% = &H1        ' Device clear state
820     REM
830     REM Error messages returned in variable IBERR%
840     EDVR% =  0         ' DOS error
850     ECIC% =  1         ' Function req GPIB-PC to be CIC
860     ENOL%    2         ' Write  function  detected   no
        Listeners
870     EADR% =  3         ' Interface  board  not
        addressed correctly
880     EARG% =  4         ' Invalid argument to function call
890     ESAC% =  5         ' Function requires GPIB-PC to be
        SAC
900     EABO% =  6         ' I/O operation aborted
910     ENEB% =  7         ' Non-existent interface board
920     EOIP% =  10        ' I/O  operation  started  before
        previous op completed
930     ECAP% = 11         ' No capability for operation
940     EFSO% = 12         ' File system operation error
950     EBUS% = 14         ' Command error during device call
960     ESTB% = 15         ' Serial poll status byte lost
```

```
970      ESRQ% = 16         ' SRQ remains asserted
980       REM
990       REM EOS mode bits
1000      BIN% = &H1000     ' Eight bit compare
1010      XEOS% = &H800     ' Send EOI with EOS byte
1020      REOS% = &H400     ' Terminate read on EOS
1030      REM
1040      REM Timeout values and meanings
1050      T10S% =   13      ' Timeout of 10 s (ideal)
1060      REM
1070      REM Miscellaneous
1080      S% = &H8          ' Parallel Poll sense bit
1090      LF% = &HA         ' Line feed character
1100      REM
1110      REM Application program variables passed to
1120      REM GPIB functions
1130      REM
1140      CMD$ = SPACE$(10)         ' command buffer
1150      RD$ = SPACE$(255)         ' read data buffer
1160      WRT$ = SPACE$(255)        ' write data buffer
1170      BNAME$ = SPACE$(7)        ' board name buffer
1180      BDNAME$ =  SPACE$(7)      ' board  or  device  name
          buffer
1190      FLNAME$ = SPACE$(50)      ' file name buffer
1200 '   ************END OF GPIB DRIVER******************
1210 '
1220      DEF SEG = 0
1230      DATA.SEGMENT = PEEK(&H511) * 256 + PEEK(&H510)
1240 BDNAME$ = "PSUPP"
1250 DEF SEG = DATA.SEGMENT 'define memory location
1260 CALL IBFIND (BDNAME$,PSUPP%)
1270 BDNAME$ = "DMM"
1280 CALL IBFIND (BDNAME$,DMM%)
1290 B$ = "F5N5Z0T1"  'set dmm to 5 1/2 digits,DC current
1300 CALL IBWRT(DMM%,B$)  'remote operation
1310 '
1320 '
1330 '   ********DAAC BASICA HEADER***********************
1340  '
1350 'NAME:  Data Acquisition And Control (DAAC)
1360 '       HEADER for BASICA
1370 '
1380 'FILE NAME:  DACHDR.BAS
1390 '
1400 'DOS DEVICE NAME:  DAAC
1410 '
1420 'RESERVED FUNCTION NAMES:
1430 '          AINM, AINS, AINSC, AOUM, AOUS,
1440 '          BINM, BINS, BITINS, BITOUS, BOUM, BOUS,
1450 '          CINM, CINS, CSET, DELAY
1460 'RESERVED DEF SEG VALUE NAME:  DSEG
```

```
1470 '
1480 'NAMES DEFINED AND USED BY HEADER:
1490 '          ADAPT%, AI, COUNT, FOUND%,
1500 '         .HNAME$, SG%, STAT%
1510 '
1520 FOUND% = 0
1530 SG% = &H2E
1540 'Start searching the interrupt vectors until you find
1550 'one that points to the DAAC device driver.
1560 'Do a DEF SEG to that segment.
1570 WHILE ((SG% <= &H3E) AND (FOUND% = 0))
1580       DEF SEG = 0
1590       DSEG = PEEK(SG%) + PEEK(SG% + 1) * 256
1600       DEF SEG = DSEG
1610       HNAME$=""
1620       FOR AI=10 TO 17
1630               HNAME$ = HNAME$ + CHR$(PEEK(AI))
1640       NEXT AI
1650       IF HNAME$ = "DAAC" AND PEEK(18)+ PEEK(19) <> 0
           THEN FOUND% = 1
1660       SG% = SG% + 4
1670       WEND
1680       IF  FOUND% = 0 THEN PRINT "ERROR: DEVICE DRIVER
           DAC.COM    NOT FOUND" : END
1690       'Initialize all function name variables for calls
1700       'to access the device driver.
1710       AINM  = PEEK(&H13) * 256 + PEEK(&H12)
1720       AINS  = PEEK(&H15) * 256 + PEEK(&H14)
1730       AINSC = PEEK(&H17) * 256 + PEEK(&H16)
1740       AOUM  = PEEK(&H19) * 256 + PEEK(&H18)
1750       AOUS  = PEEK(&H1B) * 256 + PEEK(&H1A)
1760       BINM  = PEEK(&H1D) * 256 + PEEK(&H1C)
1770       BINS  = PEEK(&H1F) * 256 + PEEK(&H1E)
1780       BITINS = PEEK(&H21) * 256 + PEEK(&H20)
1790       BITOUS = PEEK(&H23) * 256 + PEEK(&H22)
1800       BOUM   = PEEK(&H25) * 256 + PEEK(&H24)
1810       BOUS   = PEEK(&H27) * 256 + PEEK(&H26)
1820       CINM   = PEEK(&H29) * 256 + PEEK(&H28)
1830       CINS   = PEEK(&H2B) * 256 + PEEK(&H2A)
1840       CSET   = PEEK(&H2D) * 256 + PEEK(&H2C)
1850       DELAY  = PEEK(&H2F) * 256 + PEEK(&H2E)
1860 DIM V%(200)
1870 DIM N$(2000)
1880 DIM VOLT(1000)
1890 DIM CURR(1000)
1900 DIM PMAX(1000)
1910 DIM VIN%(20)
1920 Z$ = SPACE$(14)
1925 C1 = -3
1930 'initialize global variables
1940 DEV% = 9
```

```
1950 ADAPT% = 0
1960 COUNT = 1
1970 STAT% = 0
1980 DEF SEG = DSEG 'define memory location
1990 CALL DELAY (ADAPT%, COUNT, STAT%)
2000 '
2010 '   *******END OF DAAC BASICA HEADER*****************
2020 '
2030 CLS
2040 SCREEN 0
2050 CLS
2060 BEEP
2070 PRINT "THE FOLLOWING OPTIONS ARE AVAILABLE FOR USE  WITH
     THIS"
2080 PRINT "PROGRAM.  SELECT A NUMBER AND THEN ENTER  RETURN.
     NUMBER"
2090 PRINT "1 MUST BE SELECTED BEFORE NUMBER 2."
2100 PRINT
2110 PRINT "1.  RUN CALIBRATION ROUTINE."
2120 PRINT
2130 PRINT "2.  RUN SOLAR CELL PARAMETER TEST."
2140 PRINT
2150 PRINT "3.  PRINT SOLAR CELL PARAMETERS ON SCREEN."
2160 PRINT
2170 PRINT "4.  PLOT I-V CURVE ON HP 7845 PLOTTER."
2180 PRINT
2190 PRINT "5.  PLOT I-V CURVE ON RGB MONITOR."
2200 PRINT
2210 PRINT "6.  WRITE I-V DATA TO FLOPPY DISK."
2220 PRINT
2230 PRINT "7.  PRINT I-V DATA ON SCREEN."
2240 PRINT
2250 PRINT "8.  READ I-V DATA FROM FLOPPY DISK."
2260 PRINT
2270 PRINT "9.  EXIT TO SYSTEM."
2280 PRINT
2290 INPUT ">",X
2300 PRINT
2310 IF X <> 1 THEN 2340
2320 GOSUB 2620   'go to calibration subroutine
2330 GOTO 2040    'return to menu
2340 IF X <> 2 THEN 2370
2350 GOSUB 3000  'go to cell test subroutine
2360 GOTO 2040
2370 IF X <> 3 THEN 2400
2380 GOSUB 6140   'go to parameter print subroutine
2390 GOTO 2040
2400 IF X <> 4 THEN 2430
2410 GOSUB 5170   'go to HP plotting subroutine
2420 GOTO 2040
2430 IF X <> 5 THEN 2460
```

```
2440 GOSUB 5030   ´go to screen graphing subroutine
2450 GOTO 2040
2460 IF X <> 6 THEN 2490
2470 GOSUB 5990  ´go to disk write subroutine
2480 GOTO 2040
2490 IF X <> 7 THEN 2520
2500 GOSUB 4910  ´go to data print subroutine
2510 GOTO 2040
2520 IF X <> 8 THEN 2550
2530 GOSUB 6320  ´go to floppy disk read subroutine
2540 GOTO 2040
2550 IF X <> 9 THEN 2570
2560 SYSTEM
2570 PRINT "ANY INPUT MUST BE FROM 1 TO 9"
2580 BEEP
2590 INPUT "PRESS ENTER TO RETURN TO MENU >",C$
2600 GOTO 2040
2610 ´
2620 ´   ******* CALIBRATION SUBROUTINE ******************
2630 ´
2640 CLS
2650 PRINT "COMMENCING CALIBRATION ROUTINE"
2660 BEEP
2670 PRINT
2680 PRINT "CONNECT STANDARD CELL TO TEST MODULE AND PLACE"
2690 PRINT "CAL/RUN SWITCH TO CAL POSITION. ENTER THE VALUE"
2700 INPUT "OF THE STANDARD CELL VOLTAGE WHEN PROMPTED >",A
2710 PRINT
2720 CHAN% = 0: CTRL% = 0: MODE% = 0
2730 STOR% = 0: COUNT = 20: RATE = 500 ´sample @ 500 HZ
2740 STAT% = 0
2750 DEF SEG = DSEG
2760 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,VIN%(0),STAT%)
2770 VIN = 0
2780 FOR G = 0 TO 19
2790     VIN = VIN%(G) + VIN   ´average 20 samples ch0
2800 NEXT G
2810 C1 = VIN/8192 - A ´calculate constant C1
2820 PRINT "C1=";C1
2830 CHAN% = 2: CTRL% = 0: MODE% = 0
2840 STOR% = 0: COUNT = 20: RATE = 500   ´sample @ 500 HZ
2850 STAT% = 0
2860 DEF SEG = DSEG
2870 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,VIN%(0),STAT%)
2880 VIN = 0
2890 FOR G = 0 TO 19
2900     VIN = VIN%(G) + VIN   ´average 20 samples ch2
2910 NEXT G
2920 C2 = VIN/8192 - A  ´calculate constant C2
```

```
2930 PRINT "C2=";C2;"   THESE VALUES SHOULD BE NEAR 5.0"
2940 BEEP
2950 PRINT "CALIBRATION COMPLETED. PLACE THE CAL/RUN"
2960 PRINT "SWITCH IN THE RUN POSITION. PRESS ENTER TO"
2970 INPUT "RETURN TO MENU >",C$
2980 RETURN
2990 ´
3000 ´   ******* CELL TEST SUBROUTINE *******************
3002 CLS
3004 IF C1 = -3 THEN 3008
3006 GOTO 3020
3008 INPUT "RUN CALIBRATION ROUTINE FIRST.PRESS RETURN >",C$
3010 ´
3020 CLS
3030 BEEP
3040 INPUT "INPUT THE CELL IDENTIFICATION NUMBER >",CELL$
3050 PRINT
3060 INPUT "INPUT THE CELL WIDTH IN CENTIMETERS >",W
3070 PRINT
3080 INPUT "INPUT THE CELL LENGTH IN CENTIMETERS >",L
3090 BEEP
3100 PRINT
3110 PRINT "MOVE SWITCH TO `SETUP´ POSITION AND INSERT CELL"
3120 PRINT "IN  FIXTURE. SELECT N/P  OR  P/N  TYPE  AS
     APPROPRIATE."
3130 INPUT "PRESS ENTER KEY WHEN DONE >",C$
3140 CLS
3150 B = 0 ´count variable
3160 ´measure cell open circuit voltage
3170 CHAN% = 0: CTRL% = 0: MODE% = 0
3180 STOR% = 0: COUNT = 20 : RATE = 500  ´sample @ 500 hz
3190 STAT% = 0
3200 DEF SEG =DSEG
3210 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,VIN%(0),STAT%)
3220 VIN = 0
3230 FOR G = 0 TO 19
3240     VIN = VIN%(G) + VIN  ´average 20 samples ch0
3250 NEXT G
3260 VOC = VIN/8192 - C1
3270 PRINT "OPEN CIRCUIT VOLTAGE = ";VOC
3280 J = INT(VOC * 678.3459 + 1314)
3290 D = INT(VOC * 474.842 + 1314)
3300 H = INT(VOC *  20.35 + 1314)
3310 N$(J) = STR$(J): N$(J) = RIGHT$(N$(J),4)
3320 DEF SEG = DATA.SEGMENT
3330 CALL IBWRT (PSUPP%,N$(J))
3340 ´determine value of power supply output
3350 CHAN% = 2: CTRL% = 0: MODE% = 0
3360 STOR% = 0: COUNT = 10: RATE = 500 ´sample @ 500 HZ
3370 STAT% = 0
```

```
3380 DEF SEG = DSEG
3390 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,VIN%(0),STAT%)
3400 VIN = 0
3410 FOR G = 0 TO 9
3420     VIN = VIN%(G) + VIN  ´average 10 samples ch2
3430 NEXT G
3440 VOUT = VIN/4096 - C2 ´calculate output voltage
3450 PRINT "POWER SUPPLY OUTPUT = ";VOUT
3460 IF ABS(VOC - VOUT) <= .0015 THEN 3580
3470 B = B + 1
3480 IF B >= 5 THEN 3500
3490 GOTO 3170 ´reinitialize setup
3500 PRINT  "VOUT  NOT WITHIN 1.5  MILLIVOLTS  OF  VOC.
     PERFORM POWER SUPPLY CALIBRATION AS PER APPENDIX C".
3510 BEEP
3520 SYSTEM
3530 ´
3540 ´   *******END INITIALIZATION ROUTINE****************
3550 ´
3560 ´   *******CONNECT CELL TO TEST CIRCUIT**************
3570 ´
3580 BEEP
3590 BEEP
3600 PRINT "MOVE SWITCH TO `TEST´ POSITION, AND PRESS"
3610 INPUT "ENTER TO VERIFY ZERO CURRENT >",C$
3620 DEF SEG = DATA.SEGMENT
3630 CALL IBRD(DMM%,Z$) ´get current from dmm
3640 ITEST = VAL(Z$)
3650  IF  ITEST  >=  0 THEN 3700 ´verify  zero  or  positive
current
3660 J = J-1
3670 N$(J) = STR$(J) : N$(J) = RIGHT$(N$(J),4)
3680 CALL IBWRT(PSUPP%,N$(J))
3690 GOTO 3620
3700 BEEP
3710 INPUT "PRESS ENTER TO BEGIN TEST >",C$
3720 ´
3730 ´   *******PARAMETER MEASURING LOOP*****************
3740 ´
3750 CLS
3760 PRINT "NOW MEASURING CELL PARAMETERS.  WAIT 1 MINUTE
     FOR PROMPT."
3770 PRINT
3780 I = 0
3790 FOR M = J TO D STEP -2 ´measure from Voc to 70% Voc
3800 I = I + 1
3810 CHAN% = 0: CTRL% = 0: MODE% = 0
3820 STOR% = 0: COUNT = 5: RATE = 500 ´sample @ 500 hz
3830 STAT% = 0
3840 DEF SEG = DSEG
```

```
3850 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,V%(0),STAT%)
3860    VTOT = 0
3870    FOR X = 0 TO 4
3880            VTOT = V%(X) + VTOT 'average 5 samples ch0
3890    NEXT X
3900 DEF SEG =  DATA.SEGMENT
3910 CALL IBRD(DMM%,Z$)
3920 CURR(I) = VAL(Z$)   'calculate current
3930 VOLT(I) = VTOT/2048 - C1 'calculate voltage
3940 PMAX(I) = VOLT(I) * CURR(I)   'calculate power
3950 N$(M) = STR$(M):N$(M) = RIGHT$(N$(M),4)
3960 CALL IBWRT (PSUPP%,N$(M)) 'downstep power supply
3970 O = 0
3980 FOR K = 1 TO 5
3990     O = O + 1   'delay 40 ms
4000 NEXT K
4010 NEXT M
4020 '
4030 FOR M = D TO H STEP -15 'measure from 70% to 3% Voc
4040 I = I + 1
4050 CHAN% = 0: CTRL% = 0: MODE% = 0
4060 STOR% = 0: COUNT = 5: RATE = 500  'sample @ 500 hz
4070 STAT% = 0
4080 DEF SEG = DSEG
4090 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,V%(0),STAT%)
4100    VTOT = 0
4110    FOR X = 0 TO 4
4120            VTOT = V%(X) + VTOT  'average 5 samples
4130    NEXT X
4140 DEF SEG = DATA.SEGMENT
4150 CALL IBRD(DMM%,Z$)
4160 CURR(I) = VAL(Z$)  'calculate current
4170 VOLT(I) = VTOT/2048 - C1  'calculate voltage
4180 PMAX(I) = VOLT(I) * CURR(I)  'calculate power
4190 N$(M) = STR$(M):N$(M) = RIGHT$(N$(M),4)
4200 CALL IBWRT (PSUPP%,N$(M)) 'downstep power supply
4210 O = 0
4220 FOR K = 1 TO 5
4230     O = O + 1  'delay 40 ms
4240 NEXT K
4250 NEXT M
4260 '
4270 E = M
4280 FOR M = E TO 1000 STEP -2  'measure from 3% Voc to 0
4290 I = I + 1
4300 CHAN% = 0: CTRL% = 0: MODE% = 0
4310 STOR% = 0: COUNT = 5: RATE = 500  'sample @ 500 hz
4320 STAT% = 0
4330 DEF SEG = DSEG
```

```
4340 CALL AINM(ADAPT%,DEV%,CHAN%,CTRL%,MODE%,STOR%,COUNT,
     RATE,V%(0),STAT%)
4350    VTOT = 0
4360    FOR X = 0 TO 4
4370            VTOT = V%(X) + VTOT  ´average 5 samples
4380    NEXT X
4390 DEF SEG = DATA.SEGMENT
4400 CALL IBRD(DMM%,Z$)
4410 CURR(I) = VAL(Z$)   ´calculate current
4420 VOLT(I) = VTOT/2048 - Cl  ´calculate voltage
4430 PMAX(I) = VOLT(I) * CURR(I)  ´calculate power
4440 N$(M) = STR$(M):N$(M) = RIGHT$(N$(M),4)
4450 CALL IBWRT (PSUPP%,N$(M))  ´downstep power supply
4460 IF VOLT(I) < 0 THEN 4490   ´check for negative voltage
4470 NEXT M  ´if not negative, step 3 mV lower
4480 ´
4490 R = I
4500 B = M
4510 FOR M = B TO (J-20) STEP 20 ´drive power supply back
4520 N$(M) = STR$(M): N$(M) = RIGHT$(N$(M),4) ´to Voc
4530 DEF SEG = DATA.SEGMENT  ´output
4540 CALL IBWRT (PSUPP%,N$(M))
4550 NEXT M
4560 FOR M = (J-20) TO J STEP 1
4570 N$(M) = STR$(M):N$(M) = RIGHT$(N$(M),4)
4580 DEF SEG = DATA.SEGMENT
4590 CALL IBWRT (PSUPP%,N$(M))
4600 NEXT M
4610 ´
4620 ´   *******END PARAMETER MEASURING LOOP**************
4630 ´
4640 ´   *******DISCONNECT CELL FROM TEST CIRCUIT**********
4650 ´
4660 BEEP
4670 PRINT  "TESTING COMPLETED.  MOVE SWITCH FROM `TEST´
     TO `SETUP´ POSITION"
4680 PRINT "TO DISCONNECT CELL FIXTURE FROM TEST CIRCUIT.
     PRESS ENTER KEY"
4690 INPUT "WHEN DONE >",C$
4700 DEF SEG = DATA.SEGMENT
4710 B$=STR$(1314) : A$ = RIGHT$(B$,4) ´drive power supply
4720 CALL IBWRT(PSUPP%,A$)  ´to zero volts output
4730 PMAX = 0
4740 FOR T = 1 TO (J-D)
4750     IF PMAX >= PMAX(T) THEN 4780
4760     PMAX = PMAX(T)  ´find max power point
4770     VMAX = VOLT(T):IMAX = CURR(T) ´find Vmax,Imax
4780 NEXT T
4790 ISC = CURR(R-1)
4800 FF = PMAX/(VOC * ISC)
4810 EFF = (PMAX / (.1353 * L * W)) * 100
```

```
4820 ISC = (INT(ISC * 1000))/1000
4830 VOC = (INT(VOC * 1000))/1000
4840 PMAX = (INT(PMAX * 1000))/1000
4850 VMAX = (INT(VMAX * 1000))/1000
4860 IMAX = (INT(IMAX * 1000))/1000
4870 FF = (INT(FF * 1000))/1000
4880 EFF = (INT(EFF * 10))/10
4890 RETURN
4900 ´
4910 ´   *******DATA PRINT SUBROUTINE*******************
4920 ´
4930 CLS
4940 FOR I = 1 TO R-1
4950 PRINT USING "##.####";VOLT(I),CURR(I),PMAX(I)
4960 NEXT I
4970 PRINT
4980 PRINT
4990 BEEP
5000 INPUT "PRESS ENTER TO RETURN TO MENU >",C$
5010 RETURN
5020 ´
5030 ´   ******SCREEN GRAPHING SUBROUTINE****************
5040 ´
5050 SCREEN 2
5060 CLS
5070 VIEW (100,40 ) - (550,180), ,1 ´establish screen limit
5080 WINDOW (0,0) - (VOC + .1,ISC + .01) ´define scale
5090 FOR I = 1 TO R-1
5100     PSET (VOLT(I),CURR(I))  ´plot I-V curve
5110 NEXT I
5120 PRINT
5130 BEEP
5140 INPUT "PRESS ENTER TO RETURN TO MENU >",C$
5150 RETURN
5160 ´
5170 ´   *******HP PLOTTING SUBROUTINE*******************
5180 ´
5190 BEEP
5200 CLS
5210 INPUT "PRESS ENTER KEY WHEN PLOTTER IS READY >",C$
5220 CLS
5230 OPEN "COM2:9600,S,7,1,RS,CS65535,DS,CD" AS #1
5240 PRINT #1,"IN;SP1;IP2000,2400,8400,7000;"
5250 PRINT #1,"SC0,1200,0,150;"  ´initialization
5260 BEEP
5270 PRINT "DO YOU WANT OUTLINE, AXES, AND  HEADER"
5280 INPUT "INCLUDED ON THE GRAPH (Y/N) >",W$
5290 PRINT
5300 IF (W$ = "Y") OR (W$ = "y") THEN 5320
5310 GOTO 5490
5320 PRINT #1,"PU0,0PD1200,0,1200,150,0,150,0,0PU"
```

```
5330 PRINT #1,"SI.2,.3;TL1.5,0" 'print tick marks
5340 FOR X = 0 TO 1200 STEP 100
5350 PRINT #1,"PA";X,",0;XT;"
5360 IF X<100 THEN PRINT #1,"CP-1.3,-1;LB";X;CHR$(3)
5370 IF X<1000 AND X>99 THEN PRINT #1,"CP-2.3,-1;LB";X;
     CHR$(3)
5380 IF X>999 THEN PRINT #1,"CP-2.8,-1;LB";X;CHR$(3)
5390 NEXT X
5400 FOR Y = 0 TO 150 STEP 15
5410 PRINT #1,"PA 0,",Y,"YT;"
5420 IF Y<100 THEN PRINT #1,"CP-3,-.25;LB";Y;CHR$(3)
5430 IF Y>99 THEN PRINT #1,"CP-4,-.25;LB";Y;CHR$(3)
5440 NEXT Y
5450 PRINT #1,"SI.35,.5"
5460 PRINT #1,"PA400,0;CP-1,-1.8;LBVOLTAGE  (mV)"+CHR$(3)
5470 PRINT #1,"PA0,45 ;DI0,1;CP-1,1.4;LBCURRENT  (mA)"
     +CHR$(3)
5480 PRINT #1,"DI;PU"
5490 FOR I = 1 TO R-1
5500 PRINT #1,"PA";INT(VOLT(I)*1000);INT(CURR(I)*1000);"PD"
5510 NEXT I
5520 PRINT #1,"PU"
5530 BEEP
5540 INPUT "DO YOU WANT PARAMETERS INCLUDED (Y/N) >",W$
5550 PRINT
5560 IF (W$ = "Y") OR (W$ = "y") THEN 5580
5570 GOTO 5720
5580 PRINT #1,"SP2;SI.15,.25"
5590 PRINT #1,"PU;PA204,75 ;CP0,0;LBIsc  = ";ISC*1000;CHR$(3)
5600 PRINT #1,"CP;LBVoc  = ";VOC*1000;CHR$(3)
5610 PRINT #1,"CP;LBPmax = ";PMAX*1000;CHR$(3)
5620 PRINT #1,"CP;LBVmp  = ";VMAX*1000;CHR$(3)
5630 PRINT #1,"CP;LBImp  = ";IMAX*1000;CHR$(3)
5640 PRINT #1,"CP;LBF.F. = ";FF;CHR$(3)
5650 PRINT #1,"CP;LBEFF  = ";EFF;CHR$(3)
5660 PRINT #1,"PU;PA 504, 75;CP0,0;LBmA";CHR$(3)
5670 PRINT #1,"CP;LBmV"+CHR$(3)
5680 PRINT #1,"CP;LBmW"+CHR$(3)
5690 PRINT #1,"CP;LBmV"+CHR$(3)
5700 PRINT #1,"CP;LBmA"+CHR$(3)
5710 PRINT #1,"CP;CP;LB%"+CHR$(3)
5720 PRINT #1,"SP2;SI.15,.25"
5730 BEEP
5740 INPUT "DO YOU WANT CELL ID AND DATE INCLUDED (Y/N) >",W$
5750 PRINT
5760 IF (W$ = "Y") OR (W$ = "y") THEN 5780
5770 GOTO 5950
5780 PRINT #1,"PU;PA 828, 140;CP0,0;LBCELL ID: ";CELL$;
     CHR$(3)
5790 PRINT #1,"CP;LBDATE : ";DATE$;CHR$(3)
5800 BEEP
```

```
5810 INPUT "DO YOU WANT IRRADIATION STATEMENT INCLUDED  (Y/N)
     >",W$
5820 IF (W$ = "Y") OR (W$ = "y") THEN 5850
5830 GOTO 5950
5840 BEEP
5850 INPUT  "TYPE  1 FOR BEFORE IRRADIATION OR  2  FOR  AFTER
     >",ANS$
5860 IF ANS$ = "1" THEN 5890
5870 IF ANS$ = "2" THEN 5910
5880 GOTO 5950
5890 PRINT #1,"CP;LBBEFORE IRRADIATION"+CHR$(3)
5900 GOTO 5950
5910 PRINT #1,"CP;LBAFTER IRRADIATION BY"+CHR$(3)
5920 BEEP
5930 INPUT "ENTER EXPONENT FOR ELECTRON FLUENCE >",NR$
5940 PRINT #1,"CP;LB10 E"+NR$+ " electrons/cm^2 "+CHR$(3)
5950 PRINT #1,"PA0,0,;SP0;"
5960 CLOSE
5970 RETURN
5980 '
5990 '   *******DATA TO DISK WRITE SUBROUTINE*************
6000 '
6010 CLS
6020 BEEP
6030 INPUT "PLACE FLOPPY DISK IN DRIVE A.  PRESS  ENTER  WHEN
     READY >",C$
6040 FILE$ = "A:" + CELL$ + ".DAT"
6050 OPEN  FILE$ FOR OUTPUT AS #2
6060 WRITE #2,L,W
6070 FOR I = 1 TO R
6080 WRITE #2,VOLT(I), CURR(I),PMAX(I)
6090 NEXT I
6100 WRITE #2,30,30,30 'include end of file flag
6110 CLOSE
6120 RETURN
6130 '
6140 '   *******PARAMETER PRINT SUBROUTINE**************
6150 '
6160 CLS
6170 PRINT
6180 PRINT
6190 PRINT
6200 PRINT
6210 PRINT "SOLAR CELL PARAMETERS FOR CELL ";CELL$;" ARE: "
6220 PRINT
6230 PRINT "VOC=";VOC;" V","Isc=";ISC;" A","PMAX=";PMAX;" W"
6240 PRINT "IMAX=";IMAX;"   A","VMAX=";VMAX;"    V","FILL
     FACTOR=";FF
6250 PRINT "EFFICIENCY=";EFF;" %"
6260 PRINT
6270 PRINT
```

```
6280 BEEP
6290 INPUT "PRESS ENTER TO  RETURN TO MENU >",C$
6300 RETURN
6310 '
6320 '   *******FLOPPY DISK READ SUBROUTINE**************
6330 '
6340 CLS
6350 BEEP
6360 PRINT "PLACE FLOPPY DISK IN DRIVE A, AND ENTER THE NAME"
6370 INPUT "OF THE DATA FILE TO BE READ >",CELL$
6380 FILE$ = "A:" + CELL$ + ".DAT"
6390 OPEN FILE$ FOR INPUT AS #2
6400 INPUT #2,L,W
6410 I = 1: PMAX = 0
6420 INPUT #2,VOLT(I), CURR(I),PMAX(I)
6430 IF VOLT(I) > 29 THEN 6490
6440       IF PMAX >= PMAX(I) THEN 6470
6450       PMAX = PMAX(I)
6460       VMAX = VOLT(I) : IMAX = CURR(I)
6470 I = I + 1
6480 GOTO 6420
6490 CLOSE
6500 R = I
6510 ISC = CURR(R-1)
6520 VOC = VOLT(1)
6530 FF = PMAX/(VOC * ISC)
6540 EFF = (PMAX / (.1353 * L * W)) * 100
6550 ISC = (INT(ISC * 1000))/1000
6560 VOC = (INT(VOC * 1000))/1000
6570 PMAX = (INT(PMAX * 1000))/1000
6580 VMAX = (INT(VMAX * 1000))/1000
6590 IMAX = (INT(IMAX * 1000))/1000
6600 FF   = (INT(FF * 1000))/1000
6610 EFF  = (INT(EFF * 10))/10
6620 RETURN
```

APPENDIX E

PRE-IRRADIATION CELL TEST RESULTS

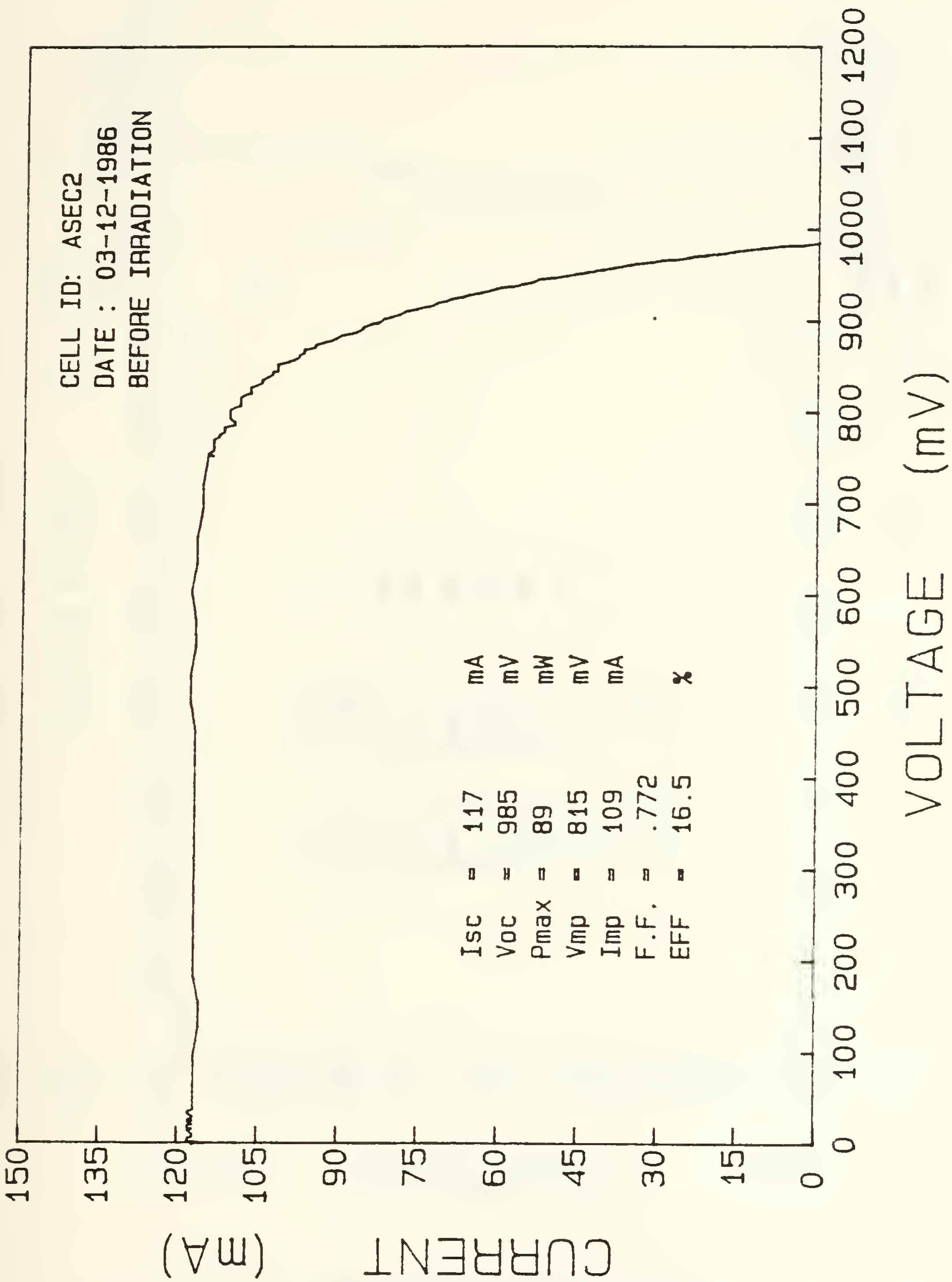


Figure 20. Pre-Irradiation I-V Curve for ASEC Cell Number 2.

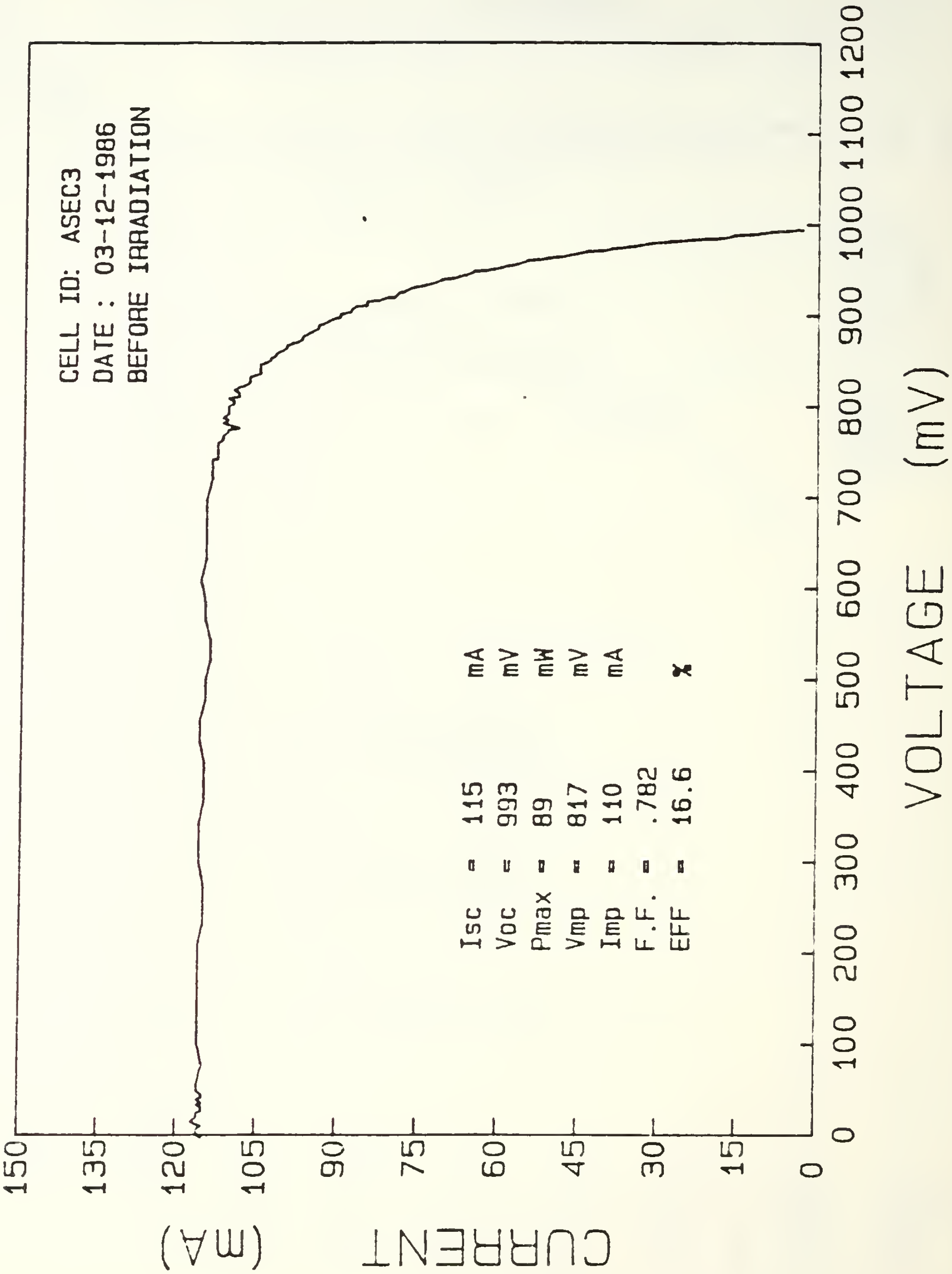


Figure 21. Pre-Irradiation I-V Curve for ASEC Cell Number 3.

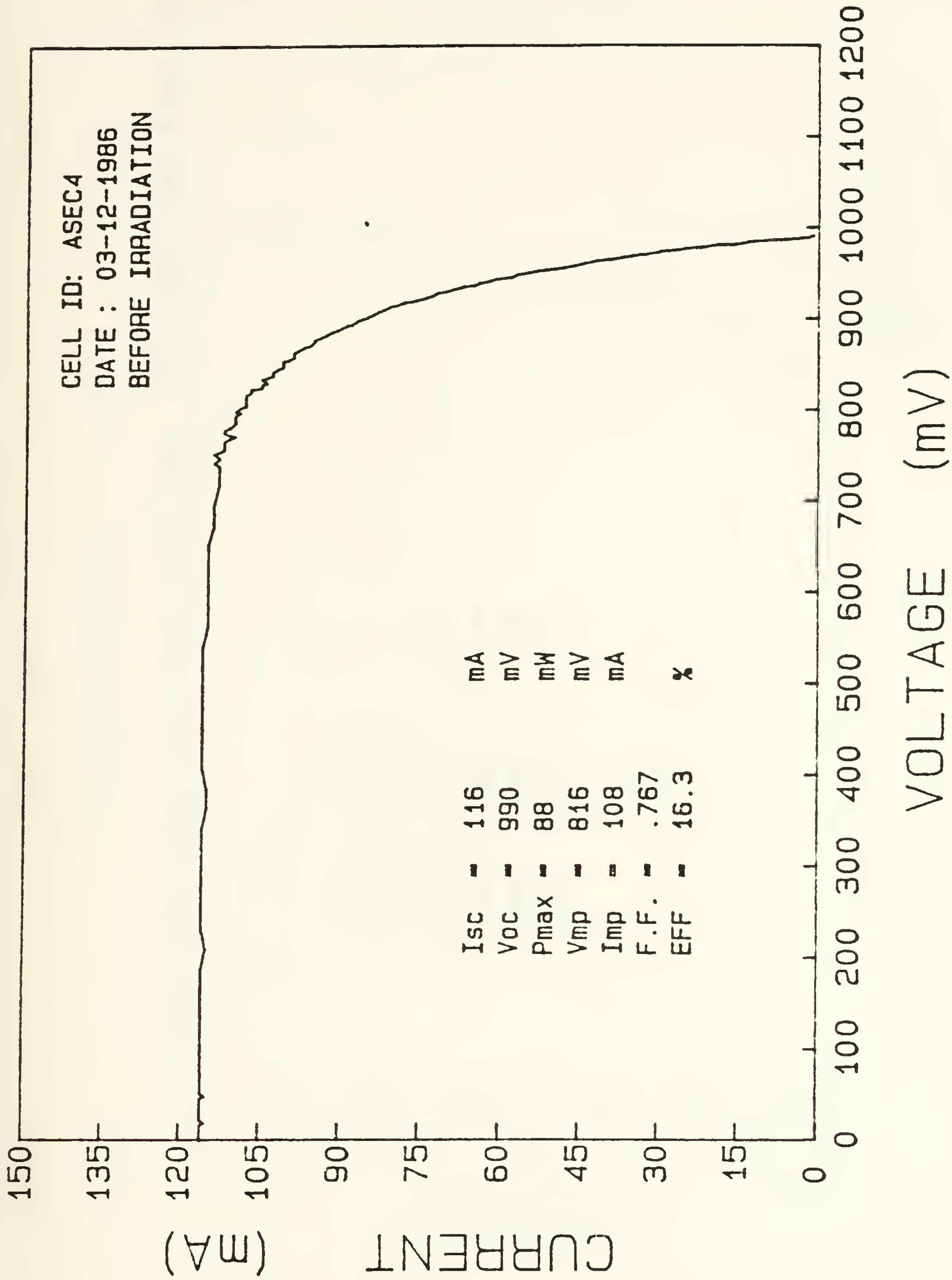


Figure 22. Pre-Irradiation I-V Curve for ASEC Cell Number 4.

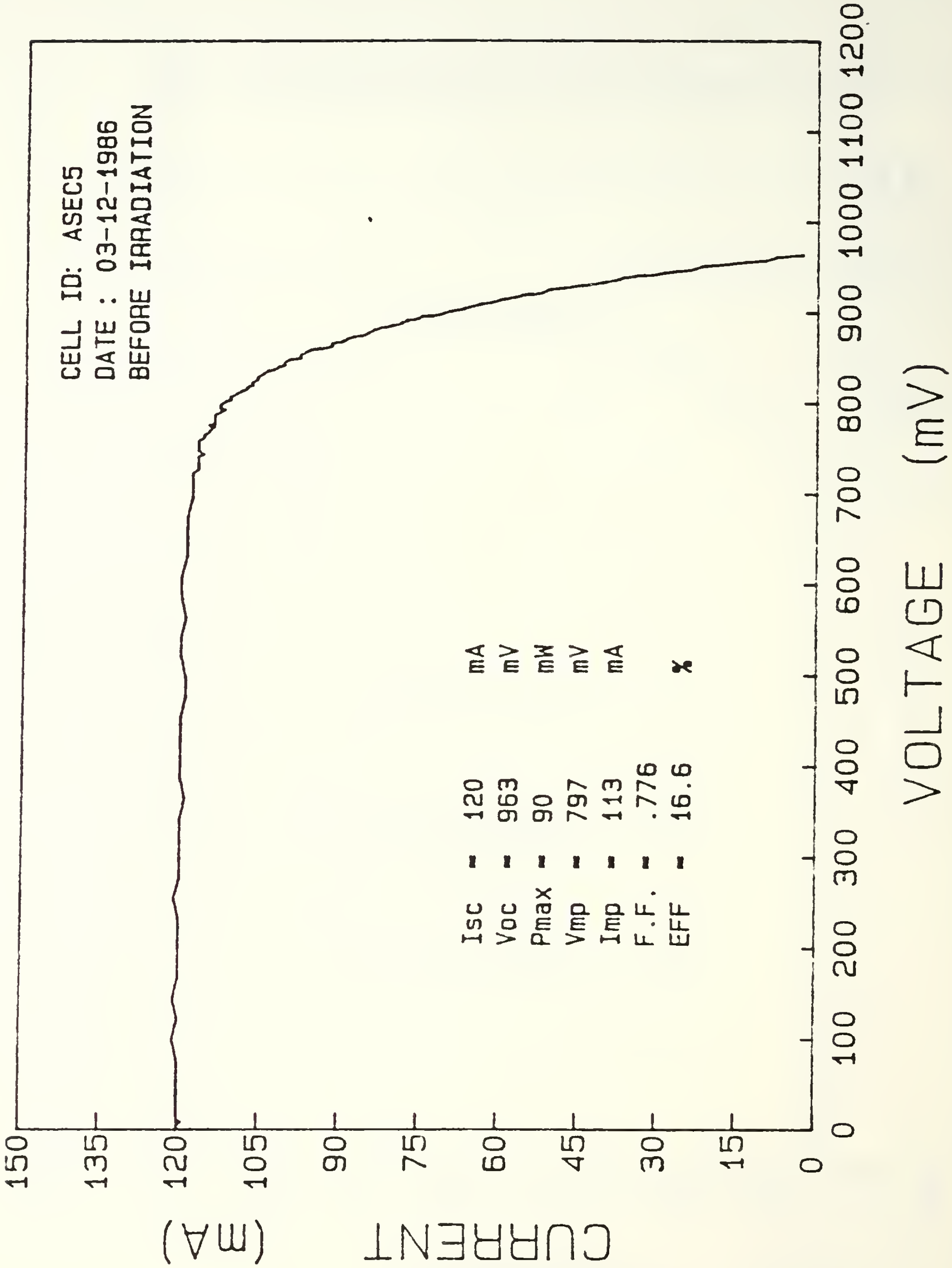


Figure 23. Pre-Irradiation I-V Curve for ASEC Cell Number 5.

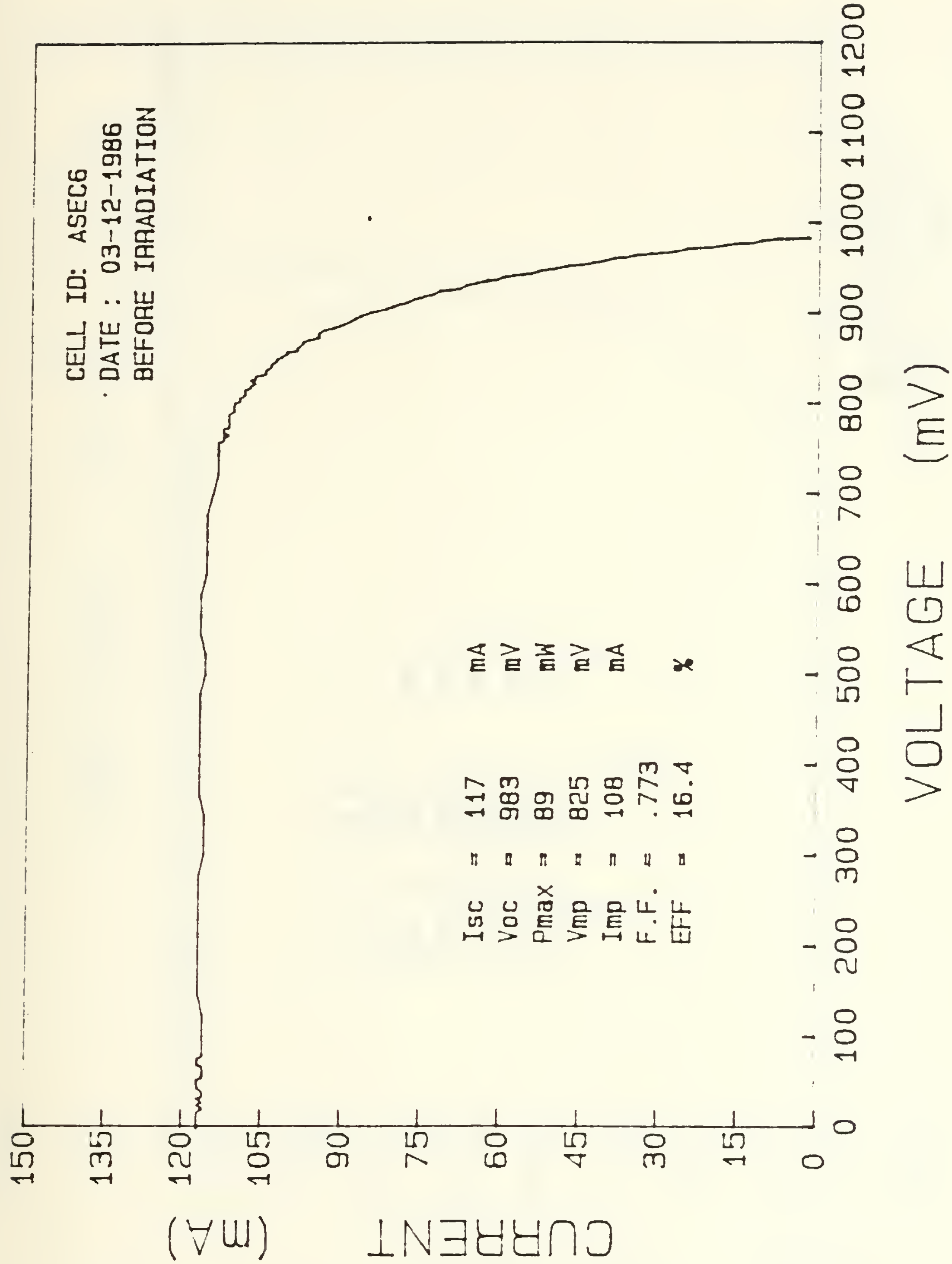


Figure 24. Pre-Irradiation I-V Curve for ASEC Cell Number 6.

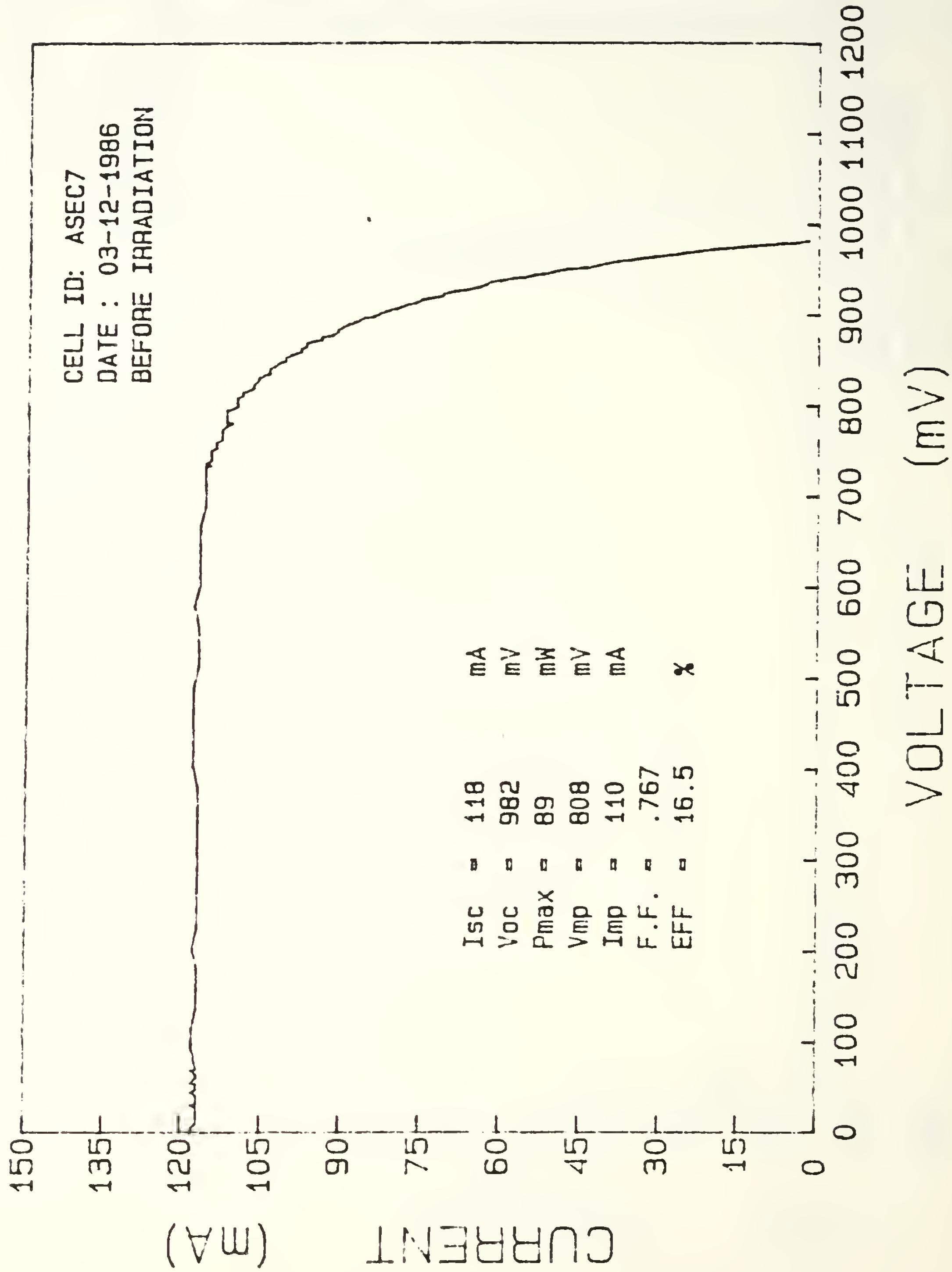


Figure 25. Pre-Irradiation I-V Curve for ASEC Cell Number 7.

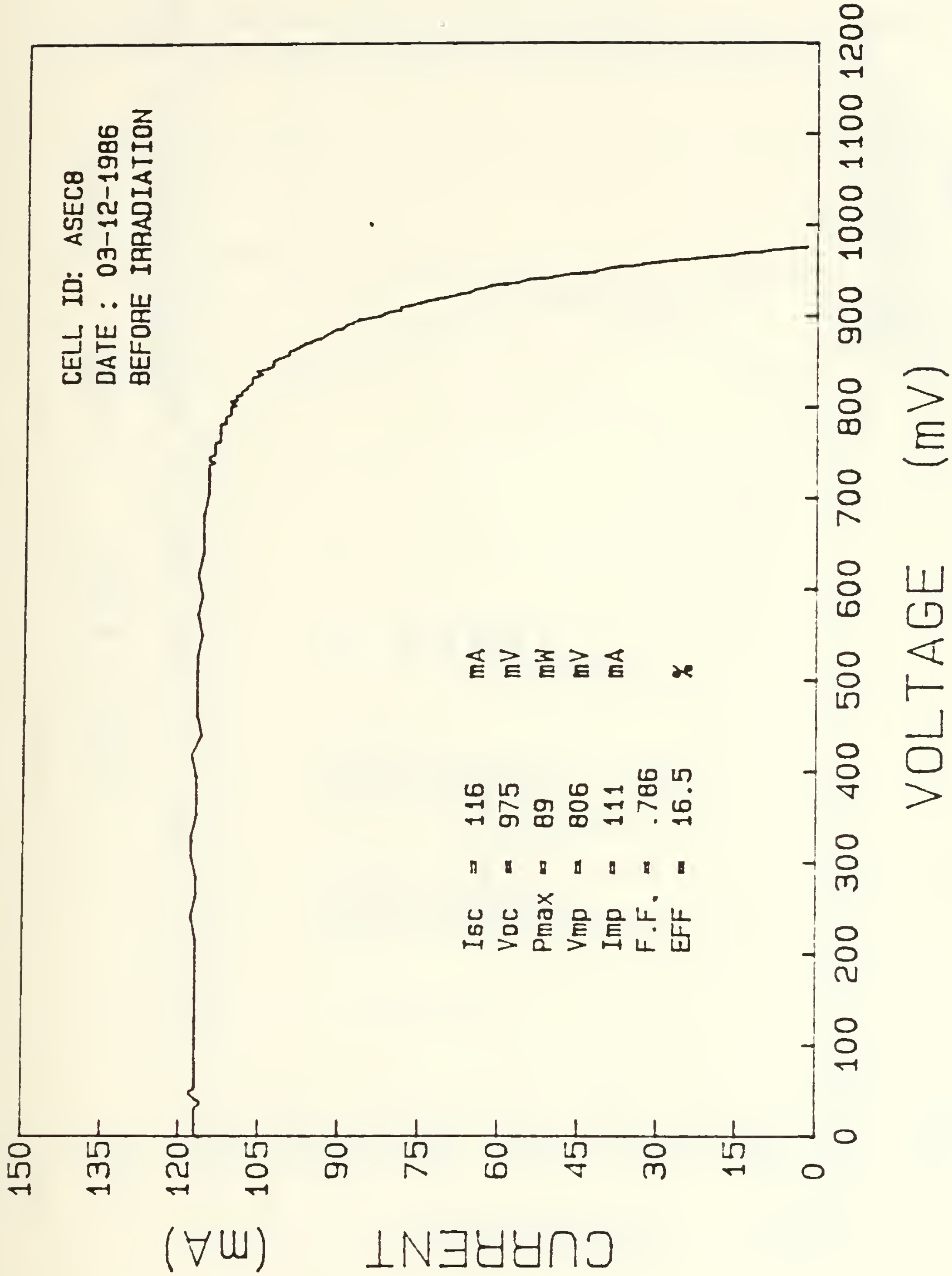


Figure 26. Pre-Irradiation I-V Curve for ASEC Cell Number 8.

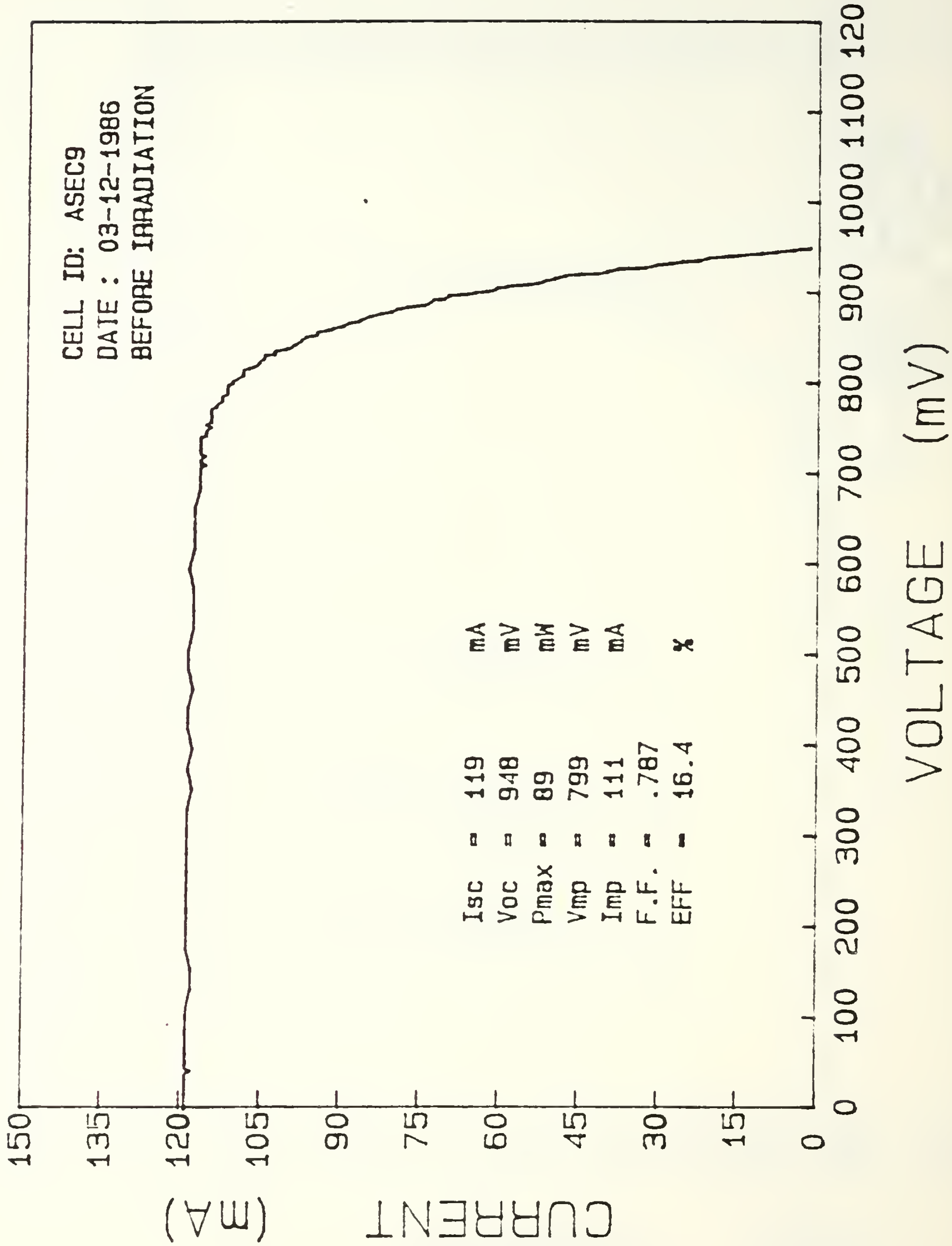


Figure 27. Pre-Irradiation I-V Curve for ASEC Cell Number 9.

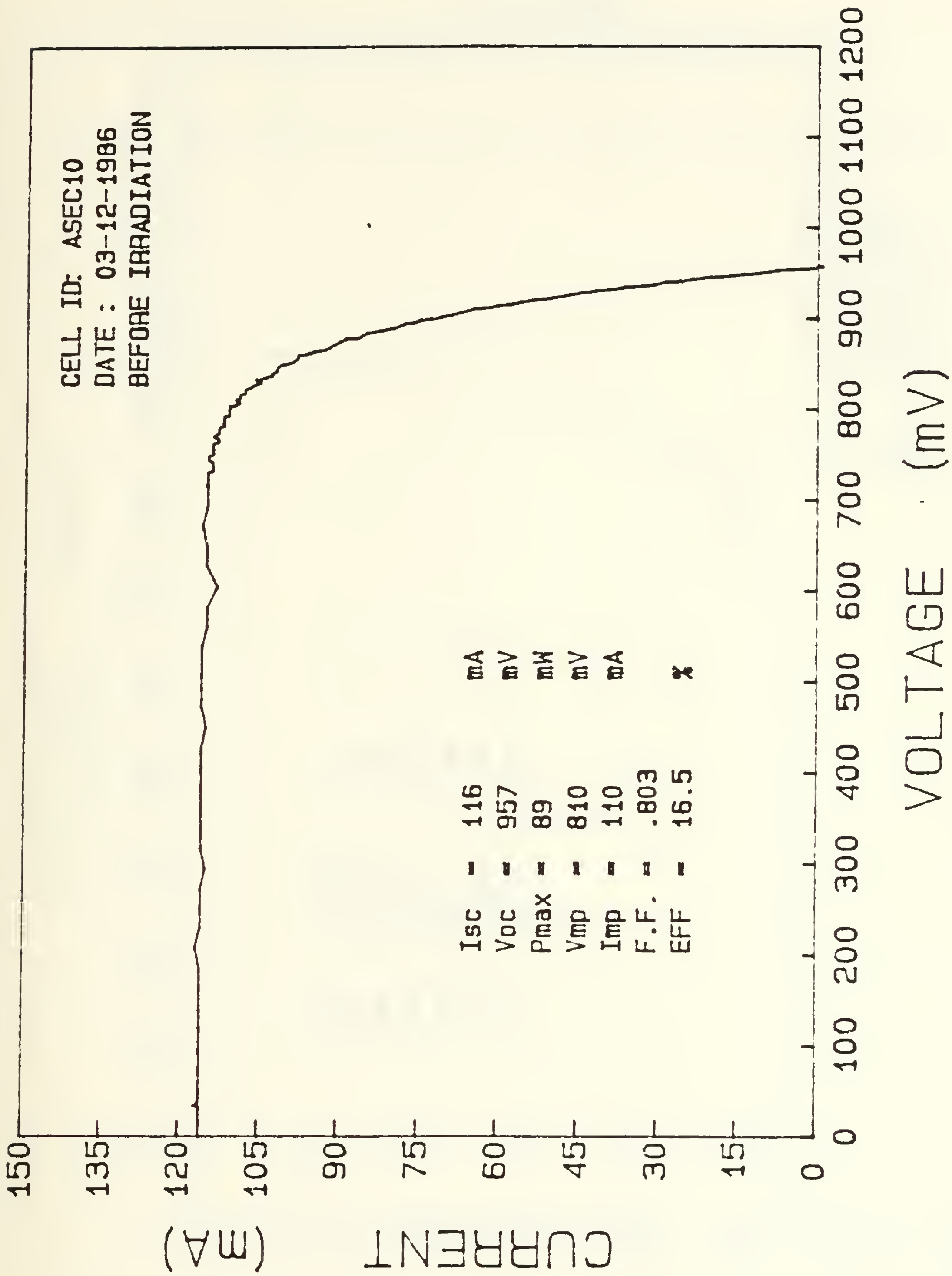


Figure 28. Pre-Irradiation I-V Curve for ASEC Cell Number 10.

APPENDIX F

POST-IRRADIATION CELL TEST RESULTS

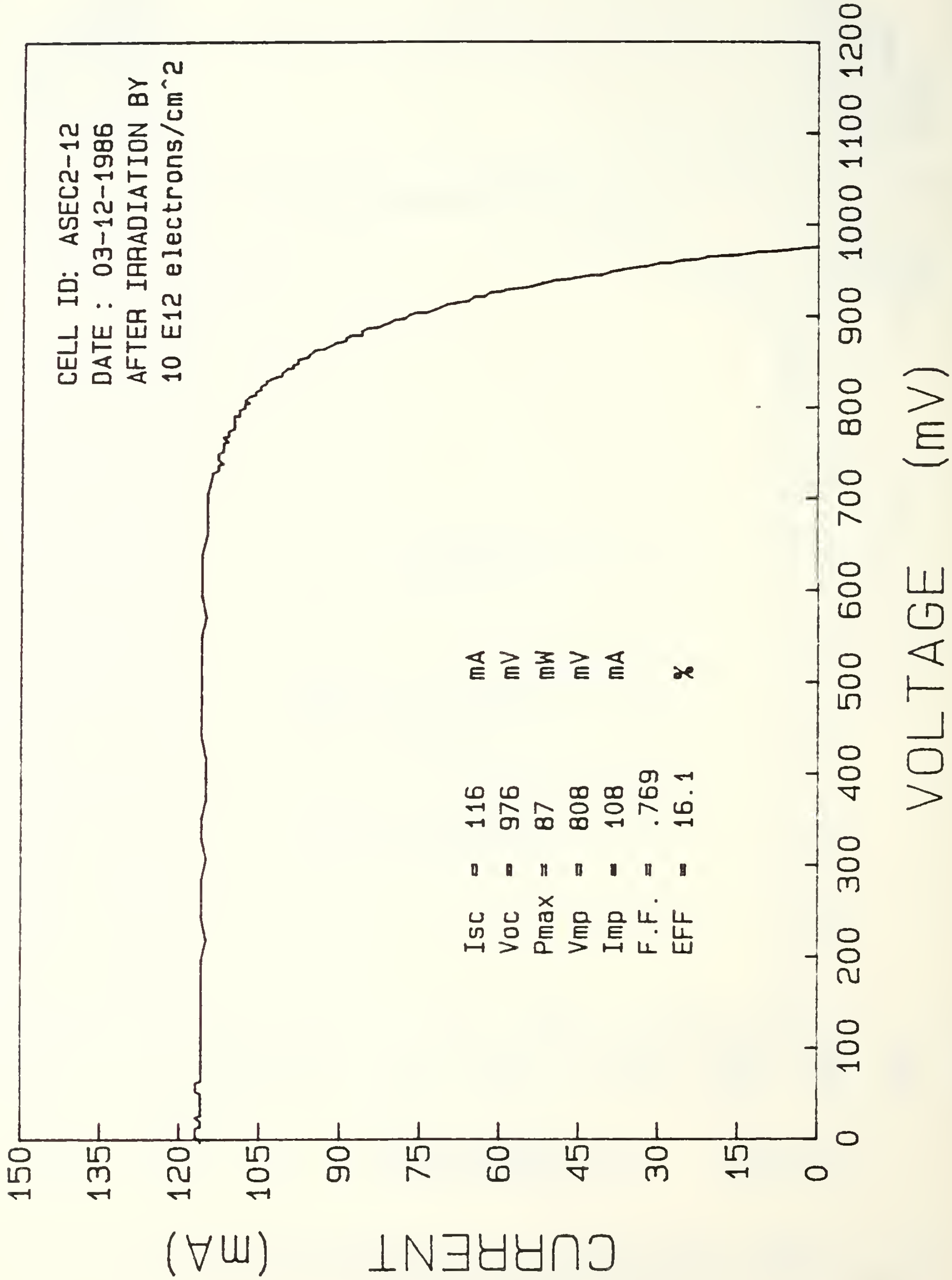


Figure 29. Post-Irradiation I-V Curve for ASEC Cell Number 2 After Irradiation by 1012 e/cm2.

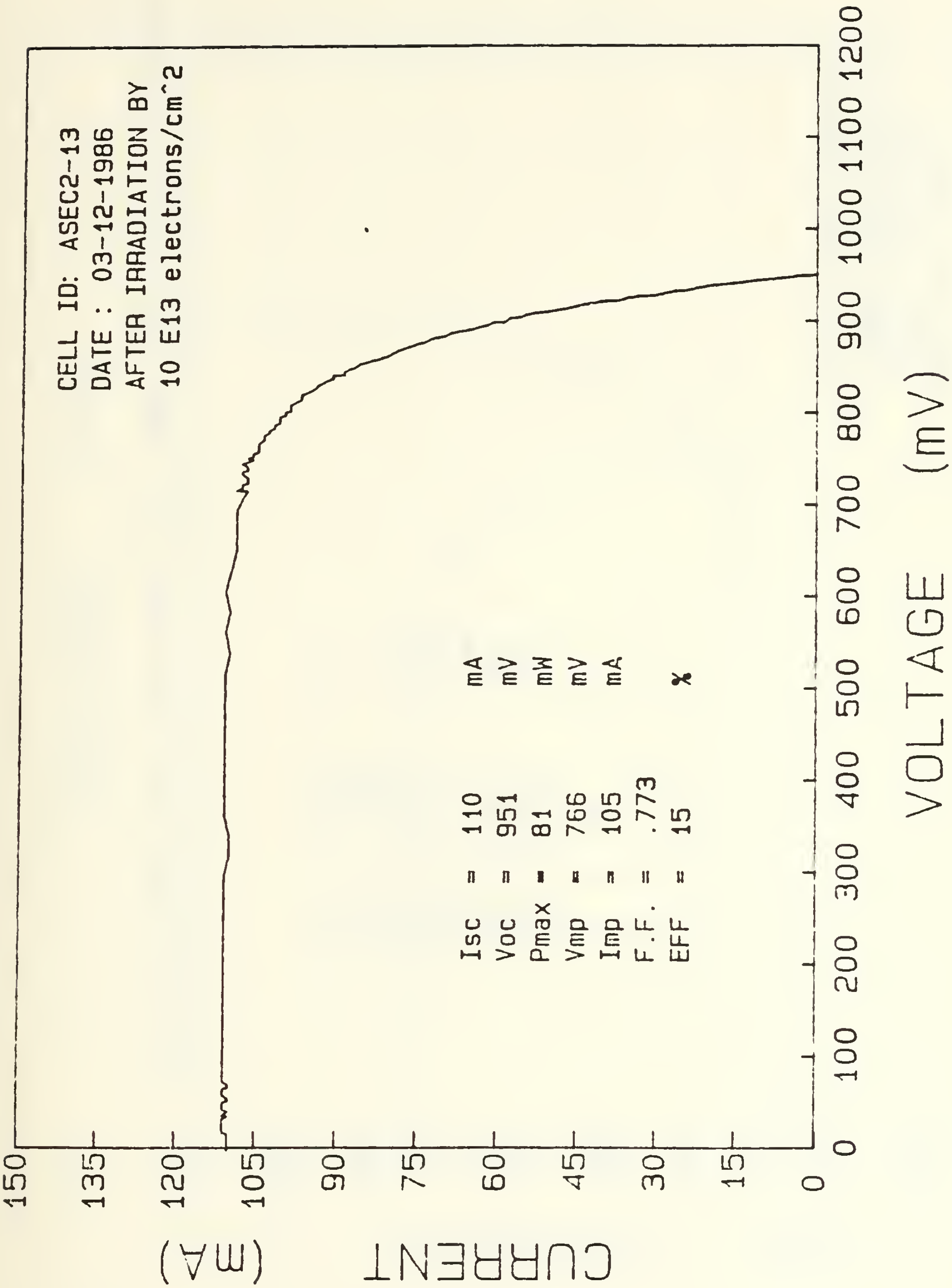


Figure 30. Post-Irradiation I-V Curve for ASEC Cell Number 2 After Irradiation by 10^{13} e/cm^2.

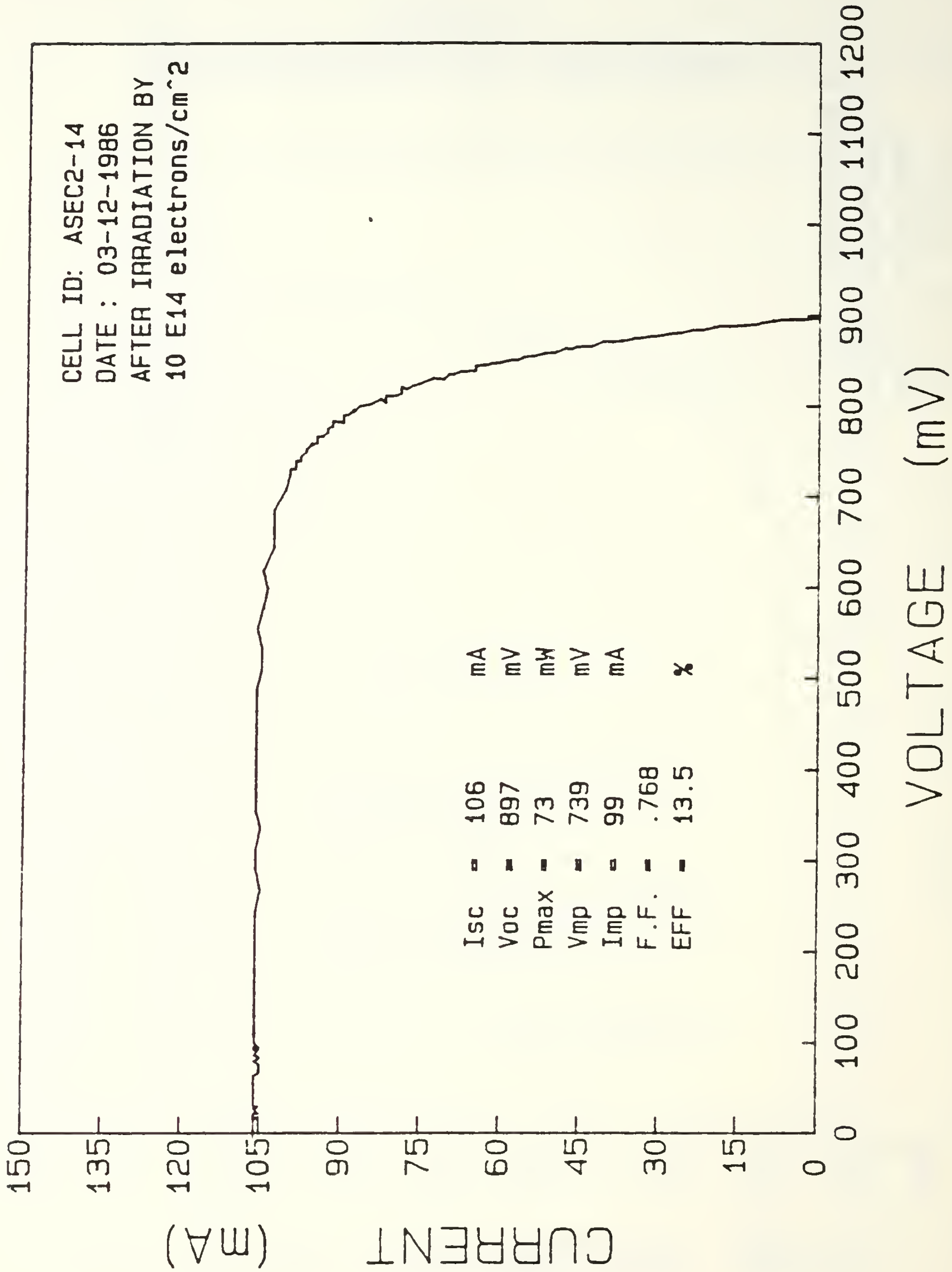


Figure 31. Post-Irradiation I-V Curve for ASEC Cell NUmber 2 After Irradiation by 10^{14} e/cm^2.

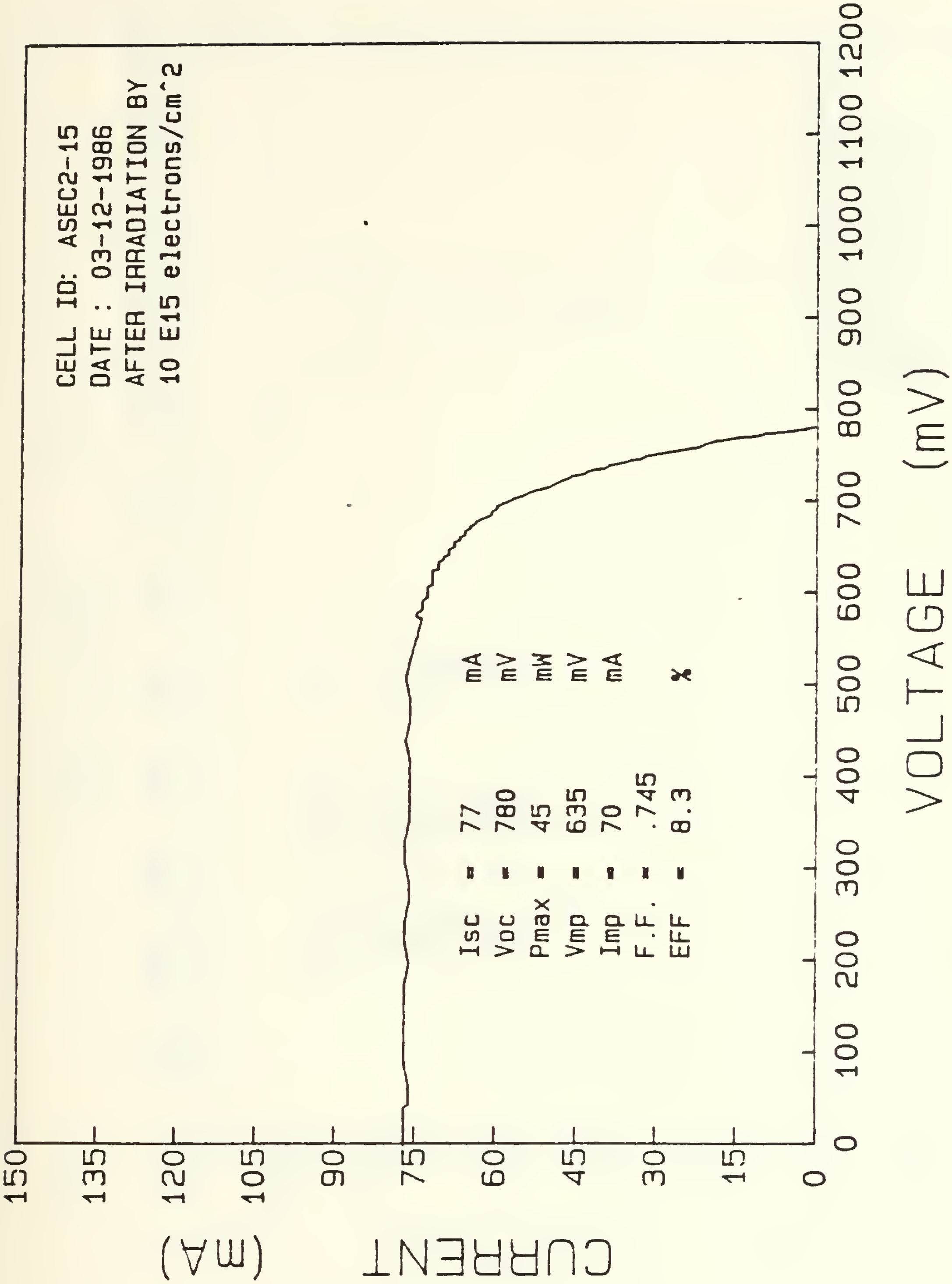


Figure 32. Post-Irradiation I-V Curve for ASEC Cell Number 2 After Irradiation by 10^{15} e/cm2.

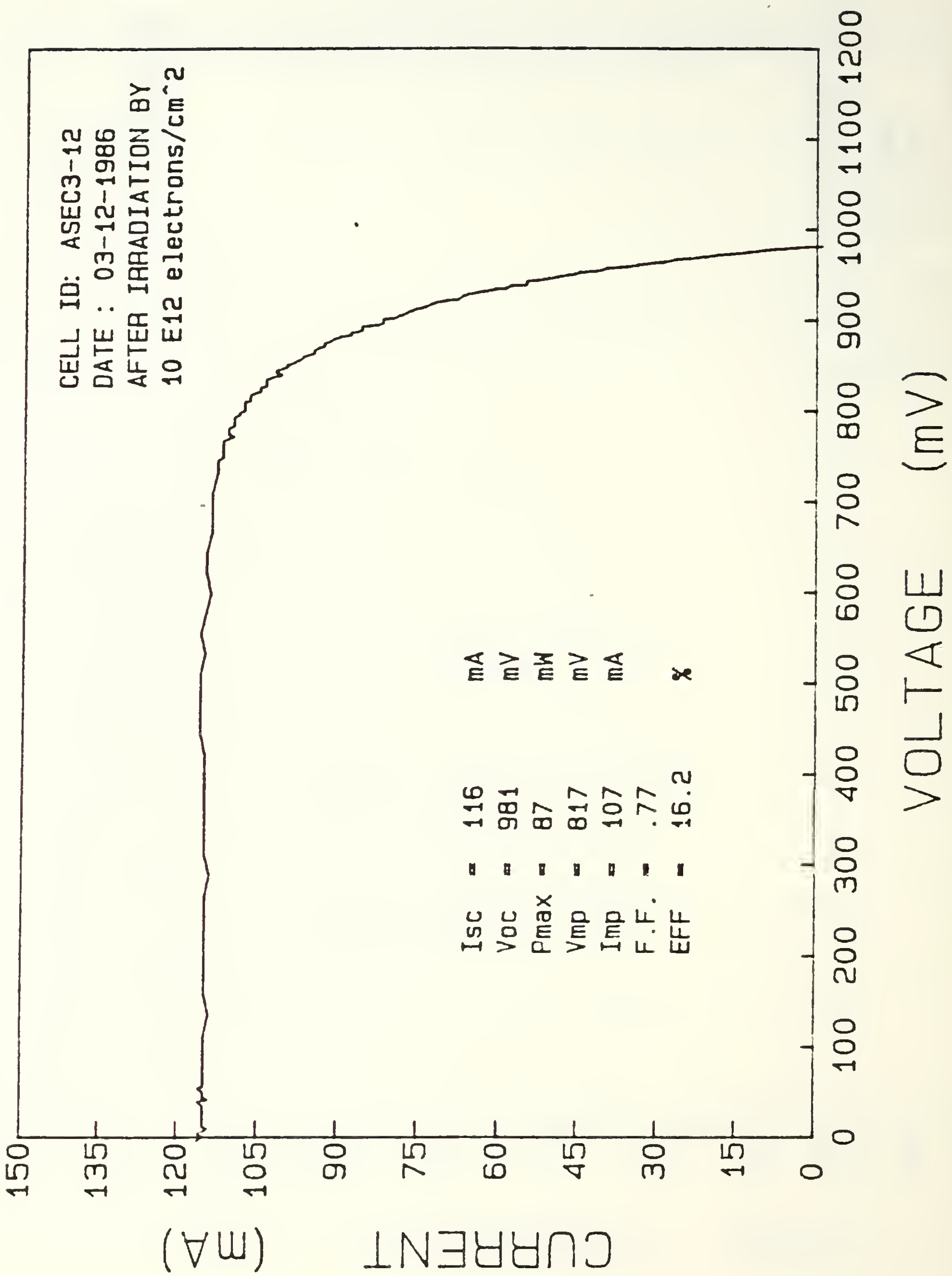


Figure 33. Post-Irradiation I-V Curve for ASEC Cell Number 3 After Irradiation by 10^{12} e/cm^2.

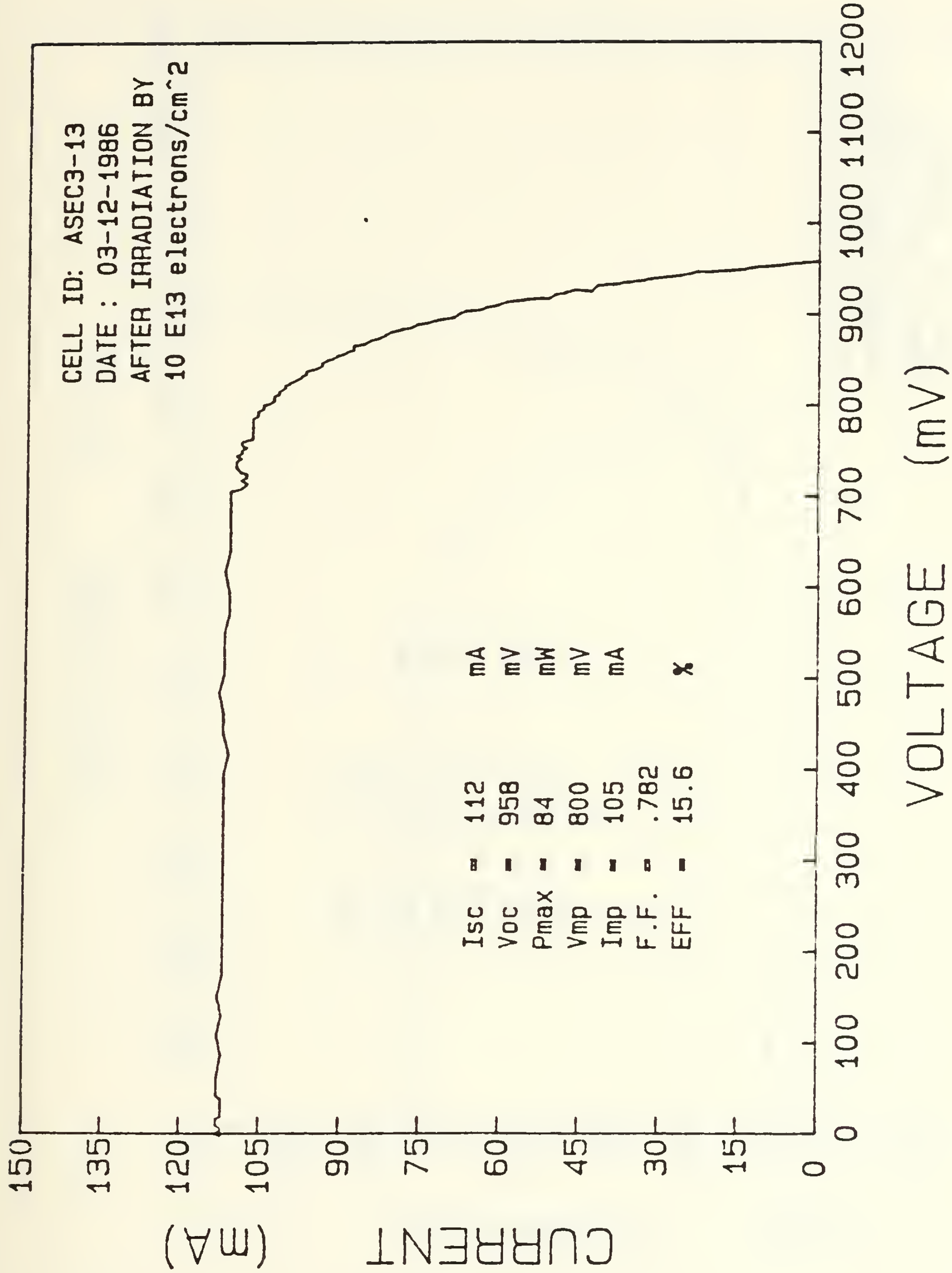


Figure 34. Post-Irradiation I-V Curve for ASEC Cell Number 3 After Irradiation by 10^{13} e/cm^2.

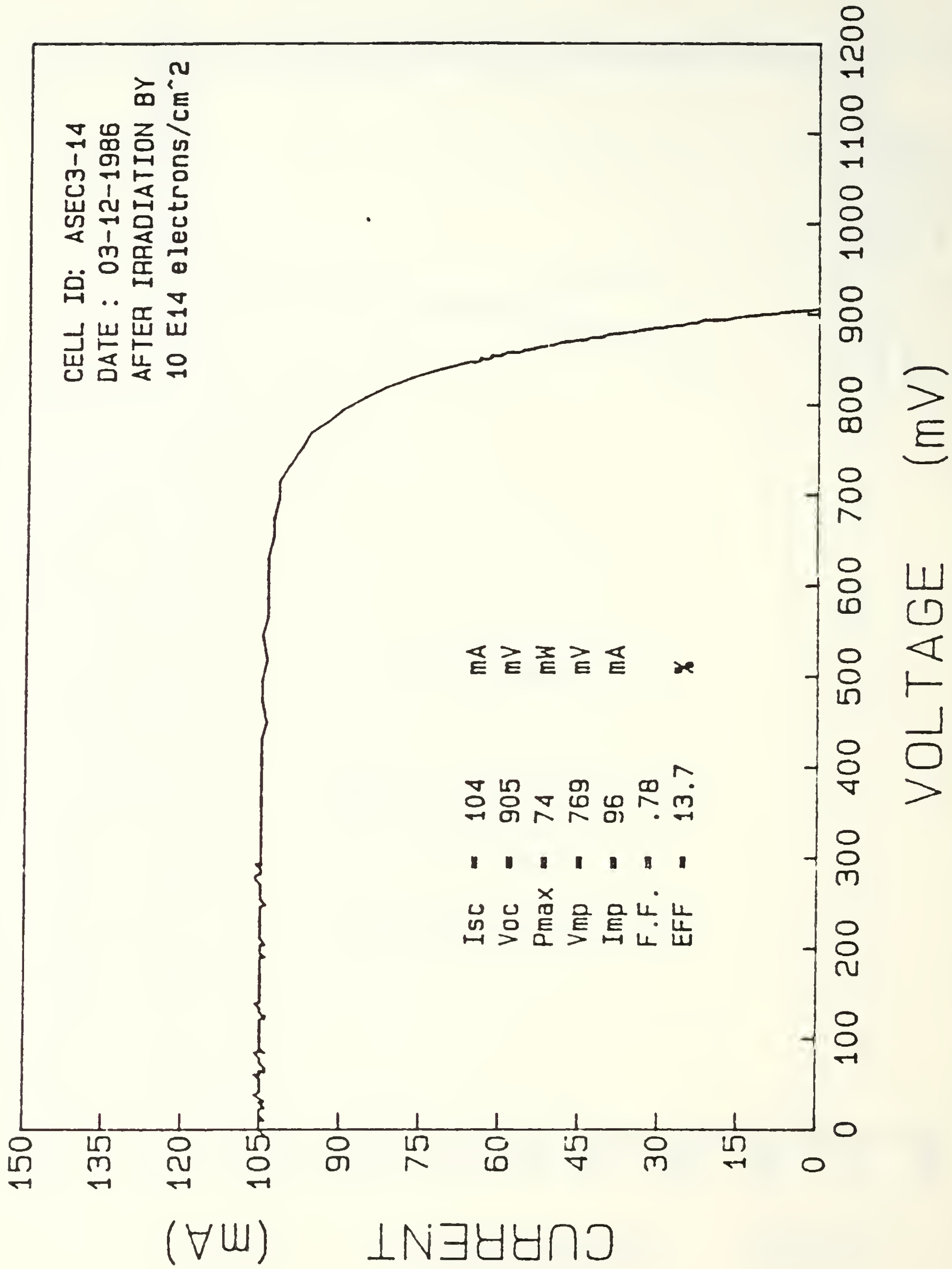


Figure 35. Post-Irradiation I-V Curve for ASEC Cell Number 3 After Irradiation by 10^{14} e/cm^2.

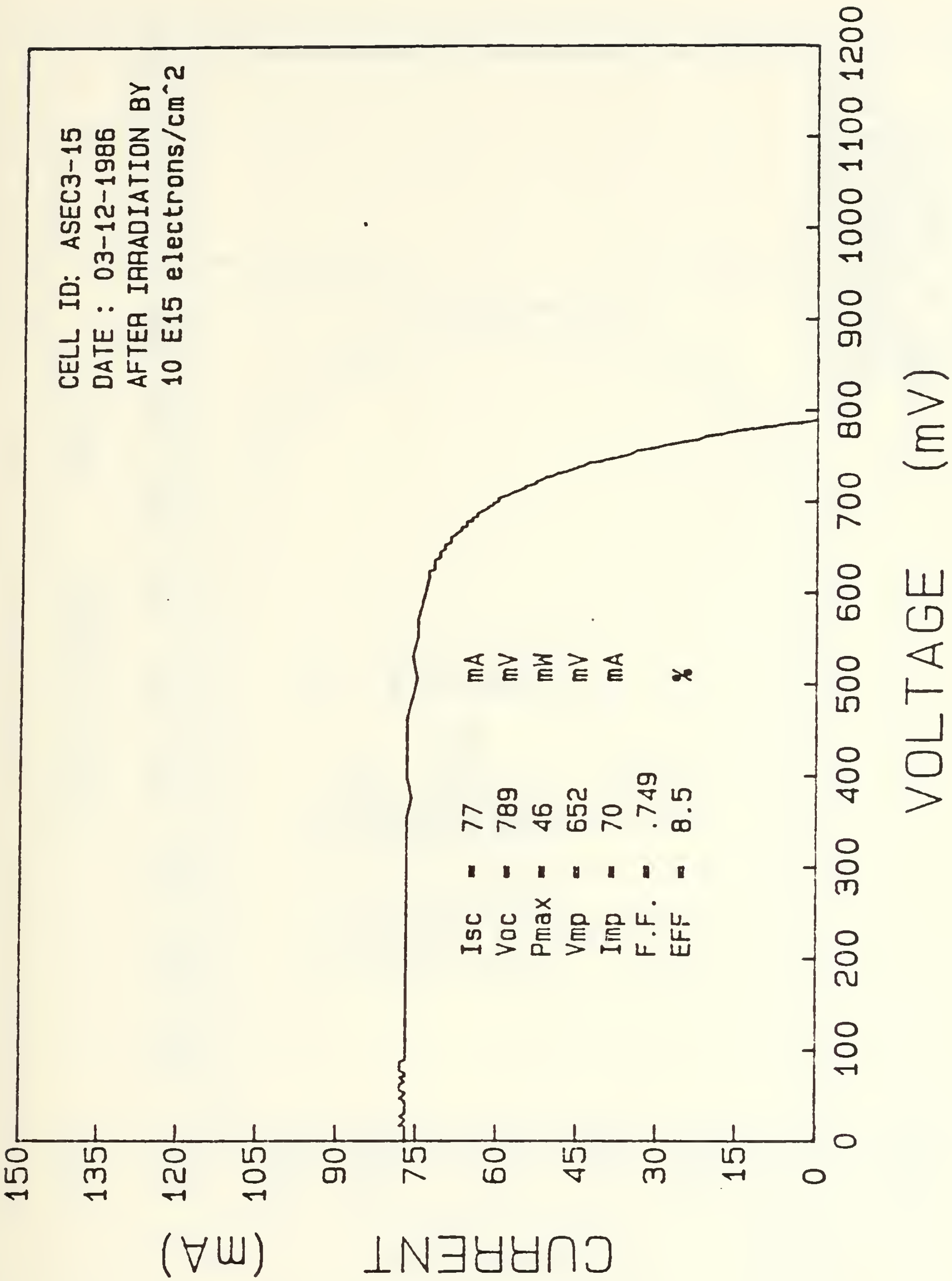


Figure 36. Post-Irradiation I-V Curve for ASEC Cell Number 3 After Irradiation by 10^{15} e/cm2.

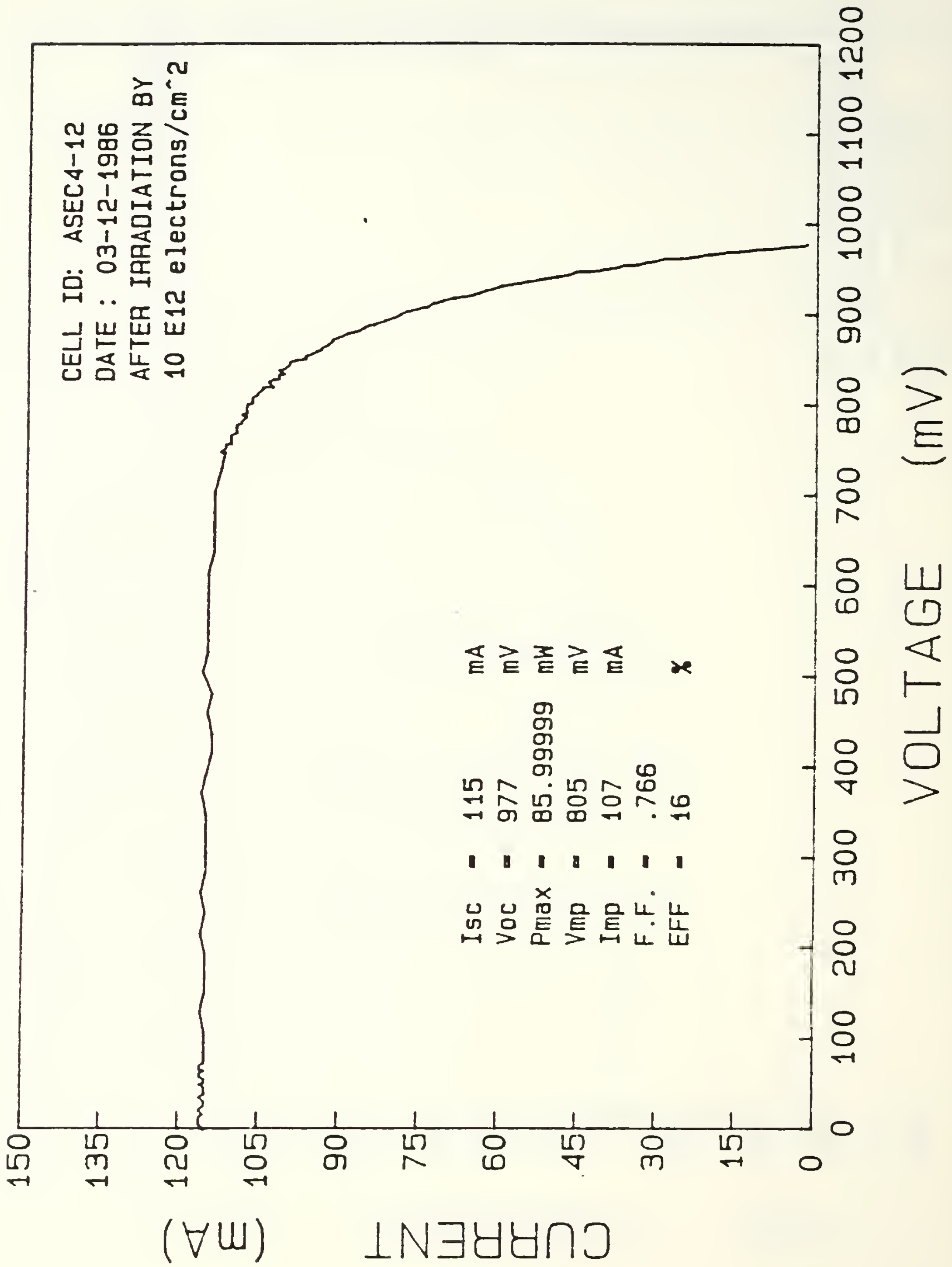


Figure 37. Post-Irradiation I-V Curve for ASEC Cell Number 4 After Irradiation by 10^{12} e/cm^2.

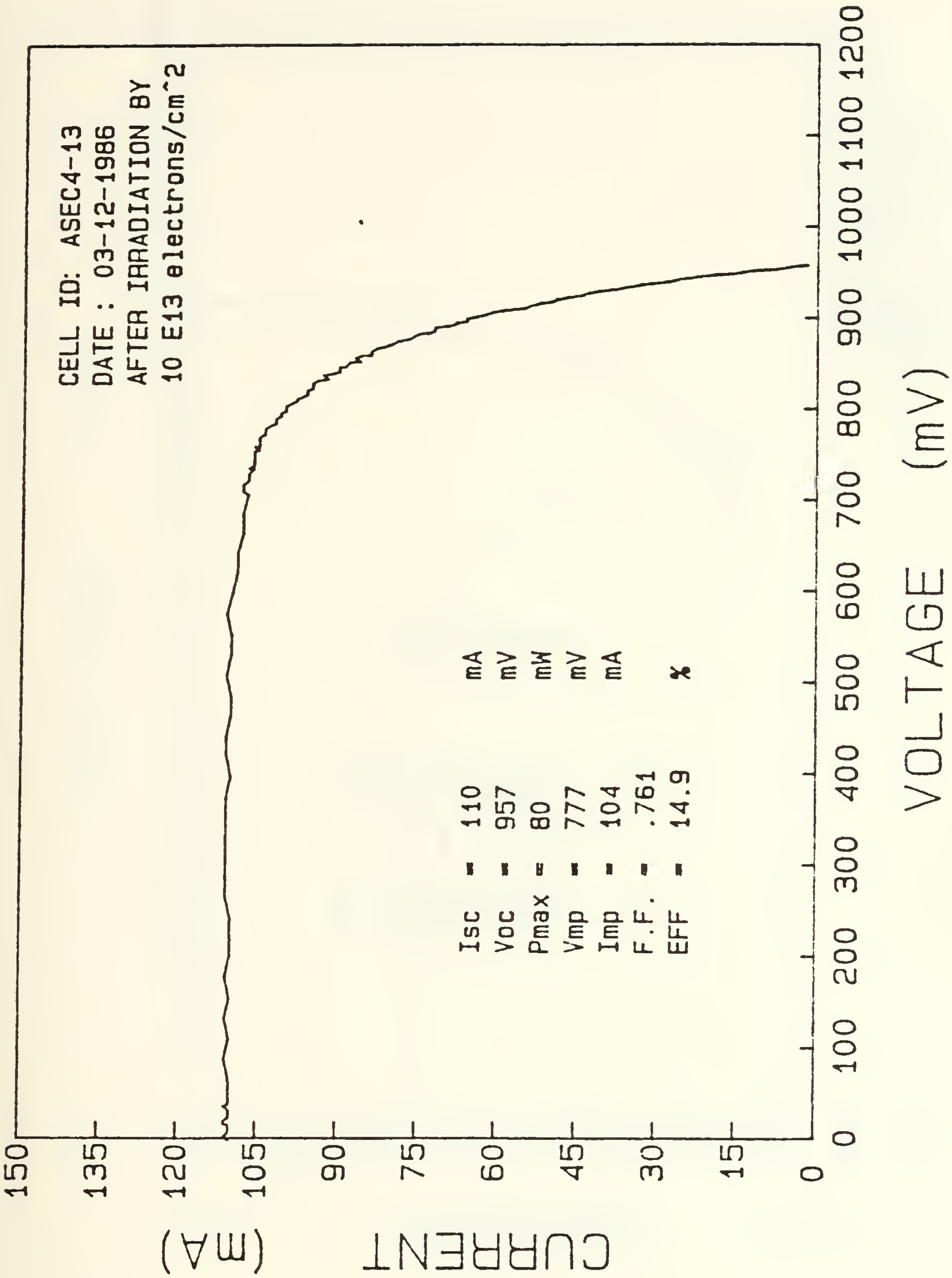


Figure 38. Post-Irradiation I-V Curve for ASEC Cell Number 4 After Irradiation by 10^{13} e/cm^2.

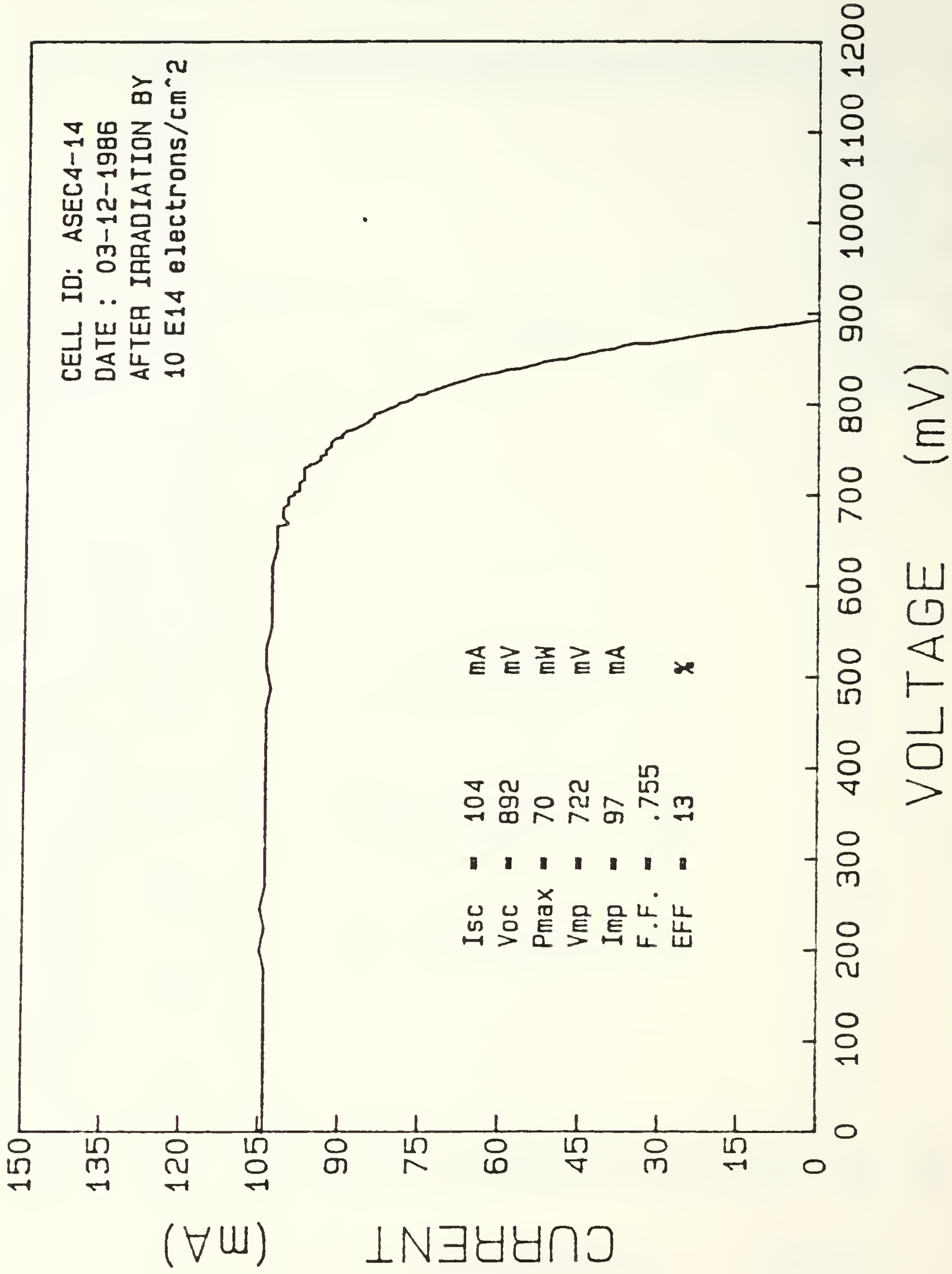


Figure 39. Post-Irradiation I-V Curve for ASEC Cell Number 4 After Irradiation by 10^{14} e/cm^2.

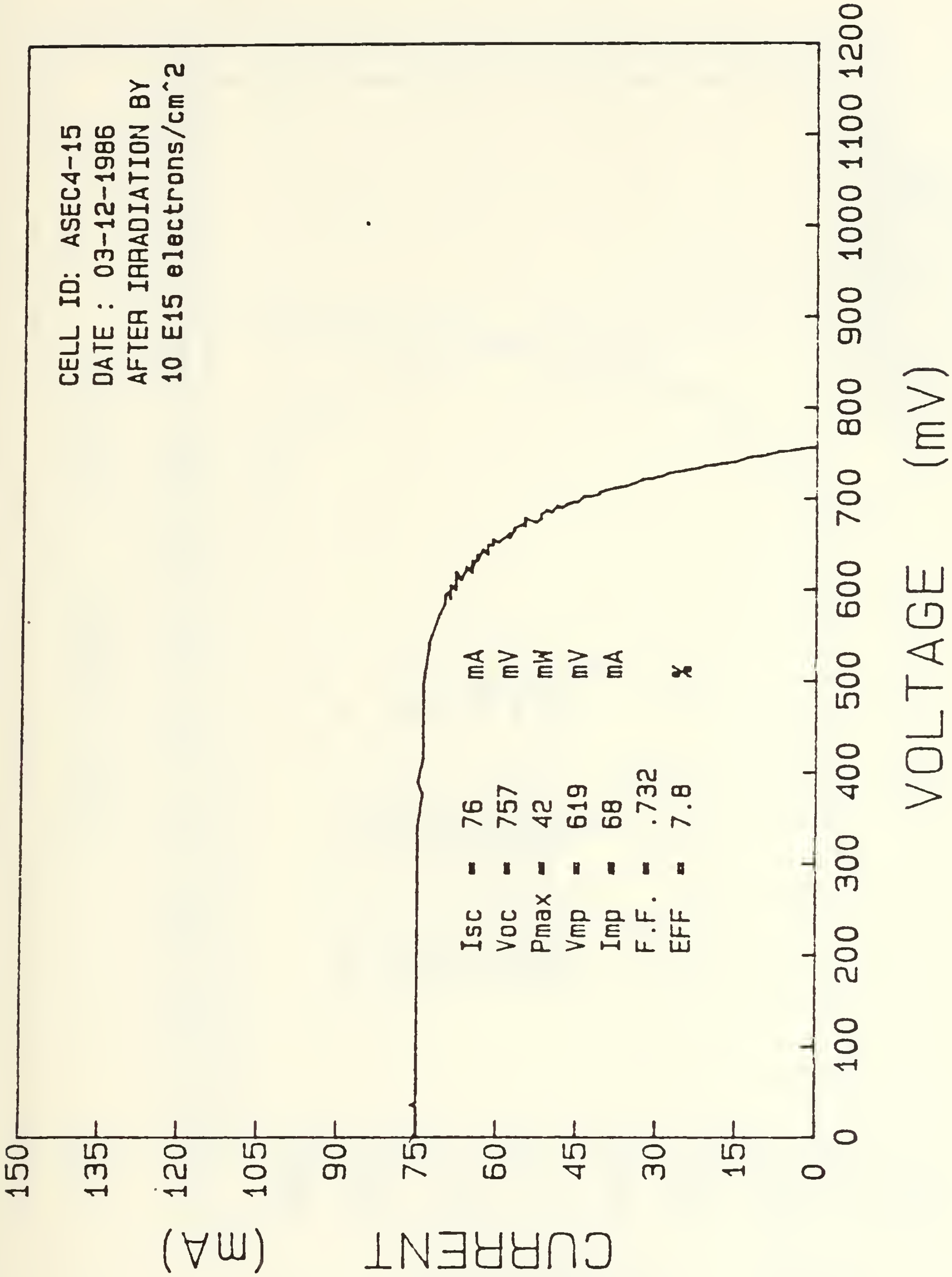


Figure 40. Post-Irradiation I-V Curve for ASEC Cell Number 4 After Irradiation by 10^{15} e/cm^2.

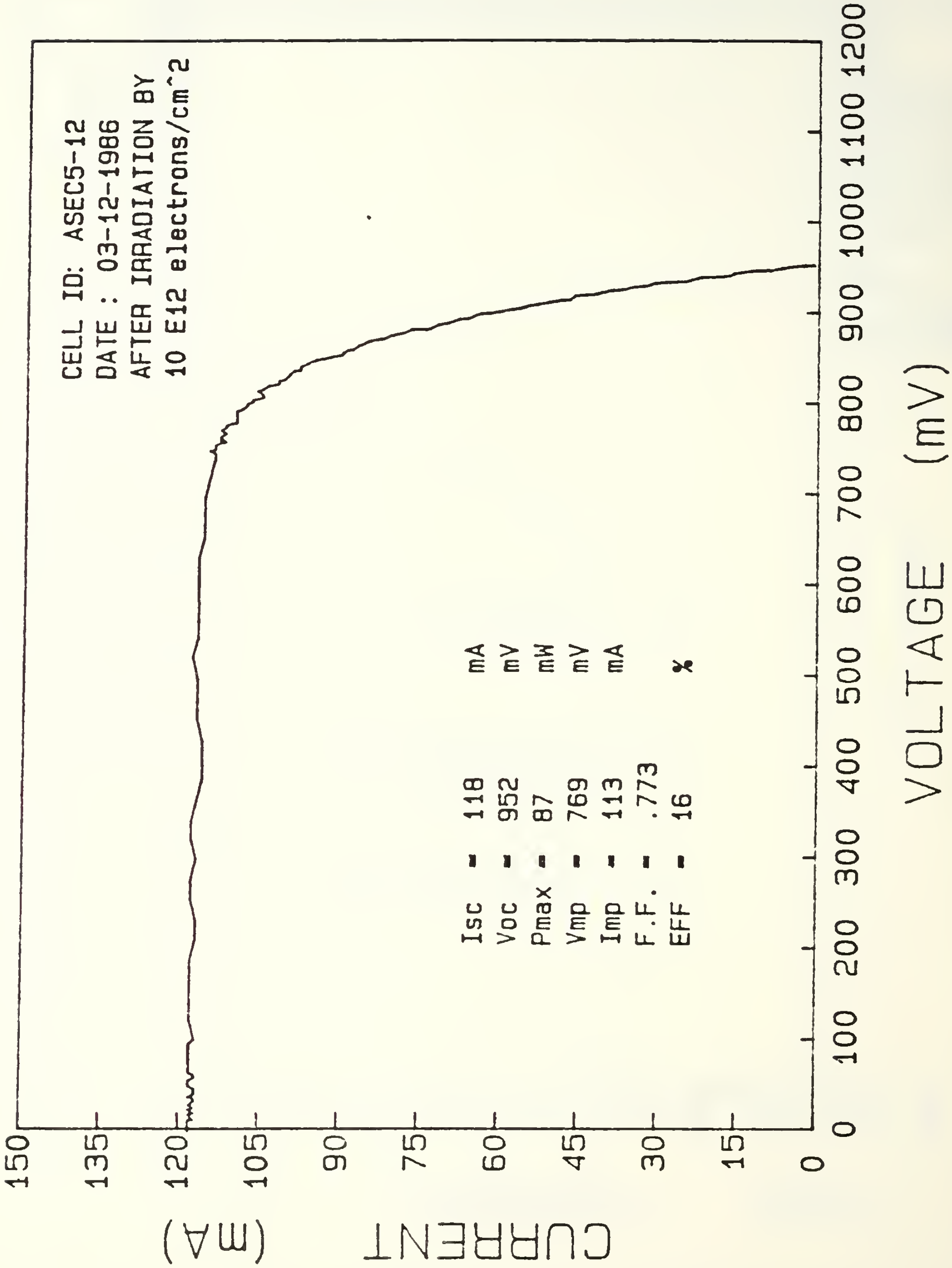


Figure 41. Post-Irradiation I-V Curve for ASEC Cell Number 5 After Irradiation by 10^{12} e/cm^2.

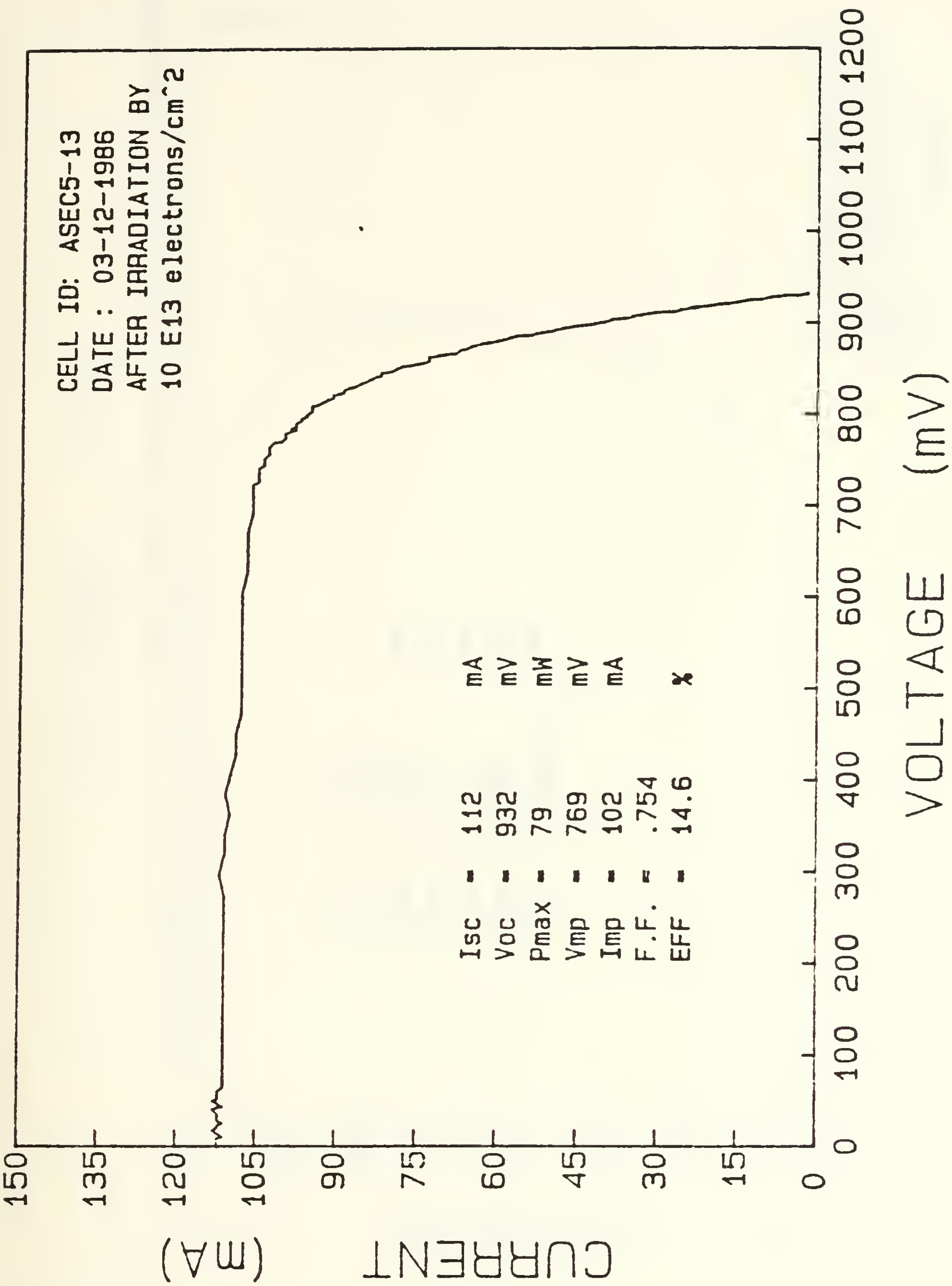


Figure 42. Post-Irradiation I-V Curve for ASEC Cell Number 5 After Irradiation by 10^{13} e/cm^2.

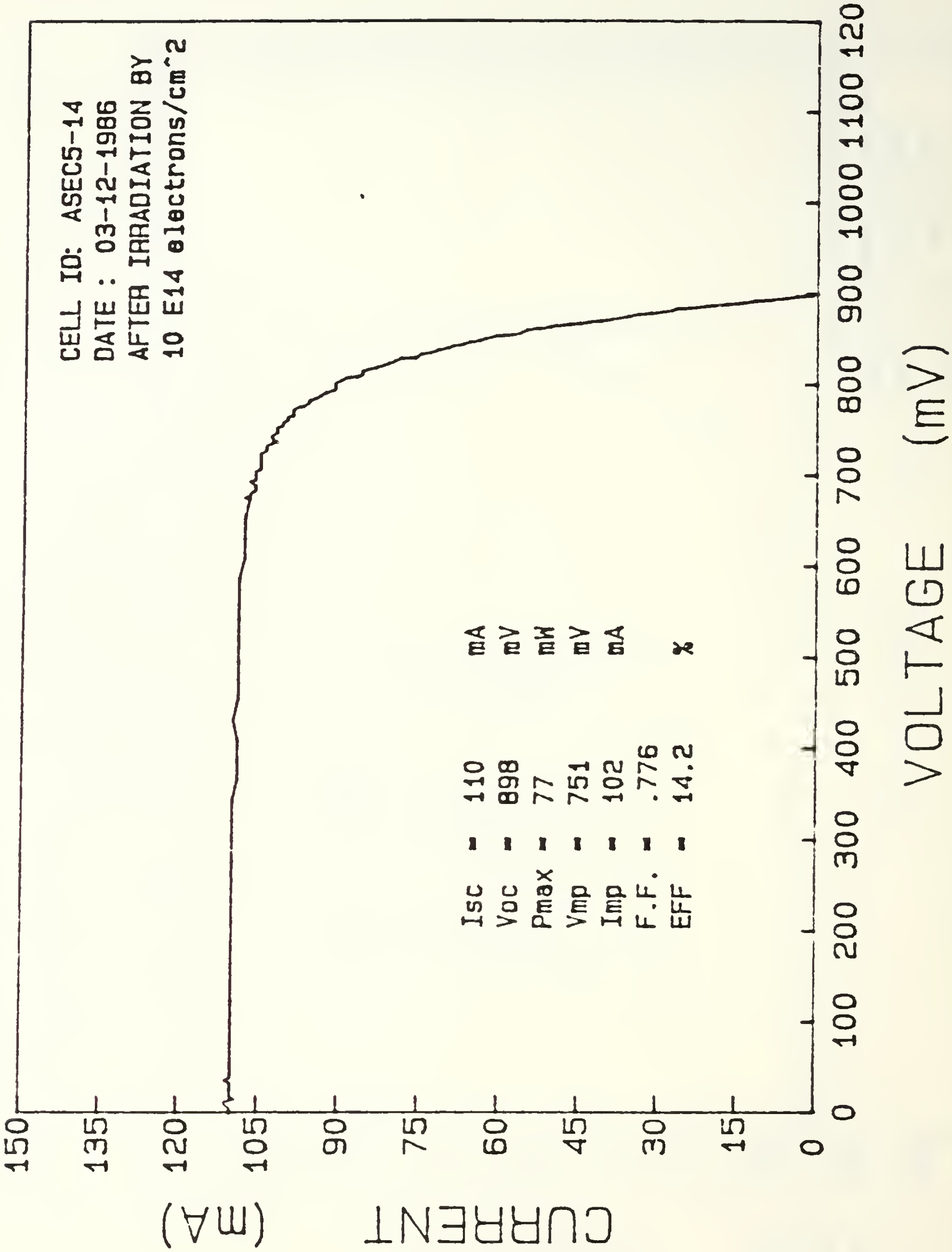


Figure 43. Post-Irradiation I-V Curve for ASEC Cell Number 5 After Irradiation by 10^{14} e/cm^{2}.

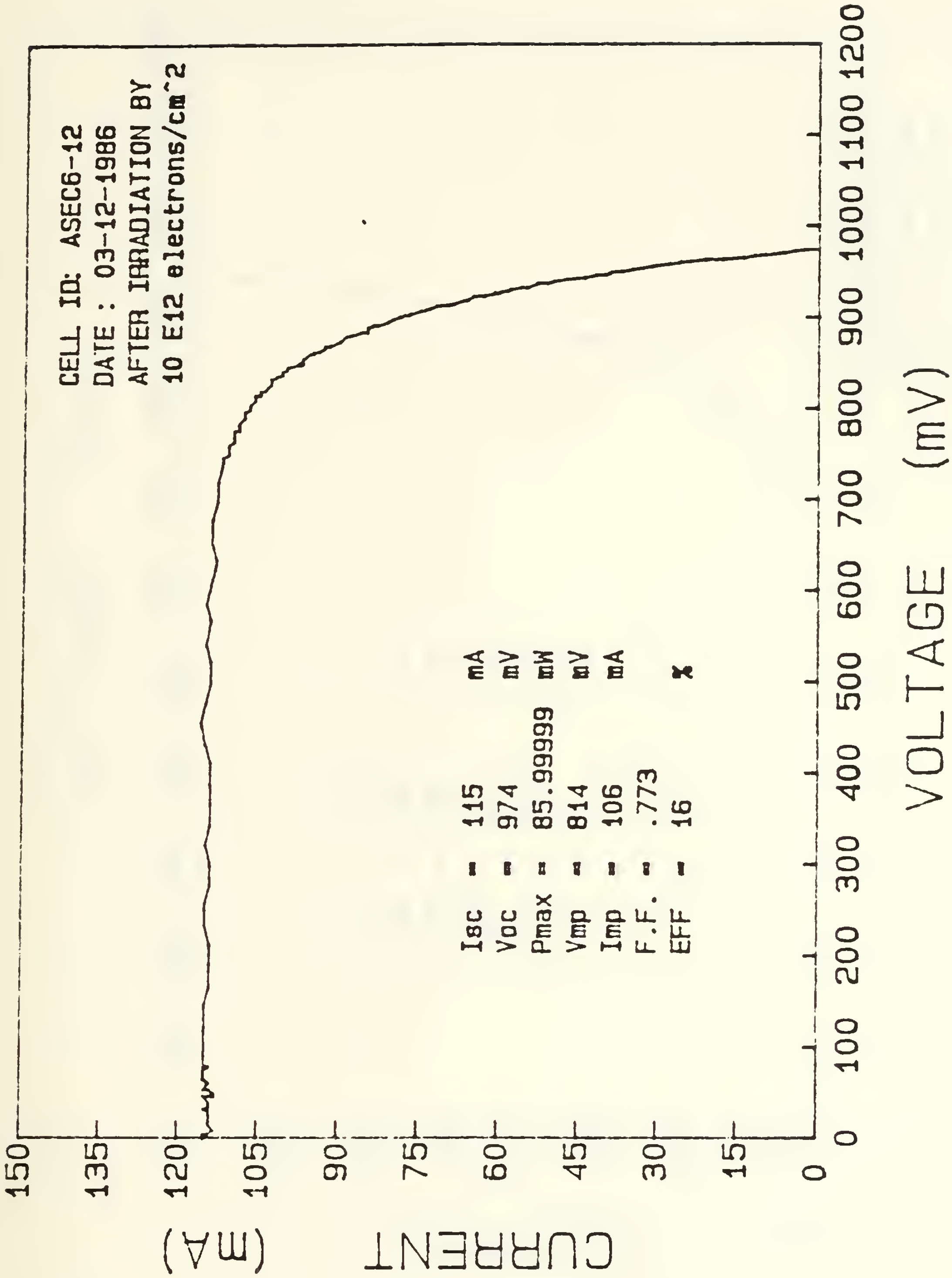


Figure 44. Post-Irradiation I-V Curve for ASEC Cell Number 6 After Irradiation by 10^{12} e/cm^2.

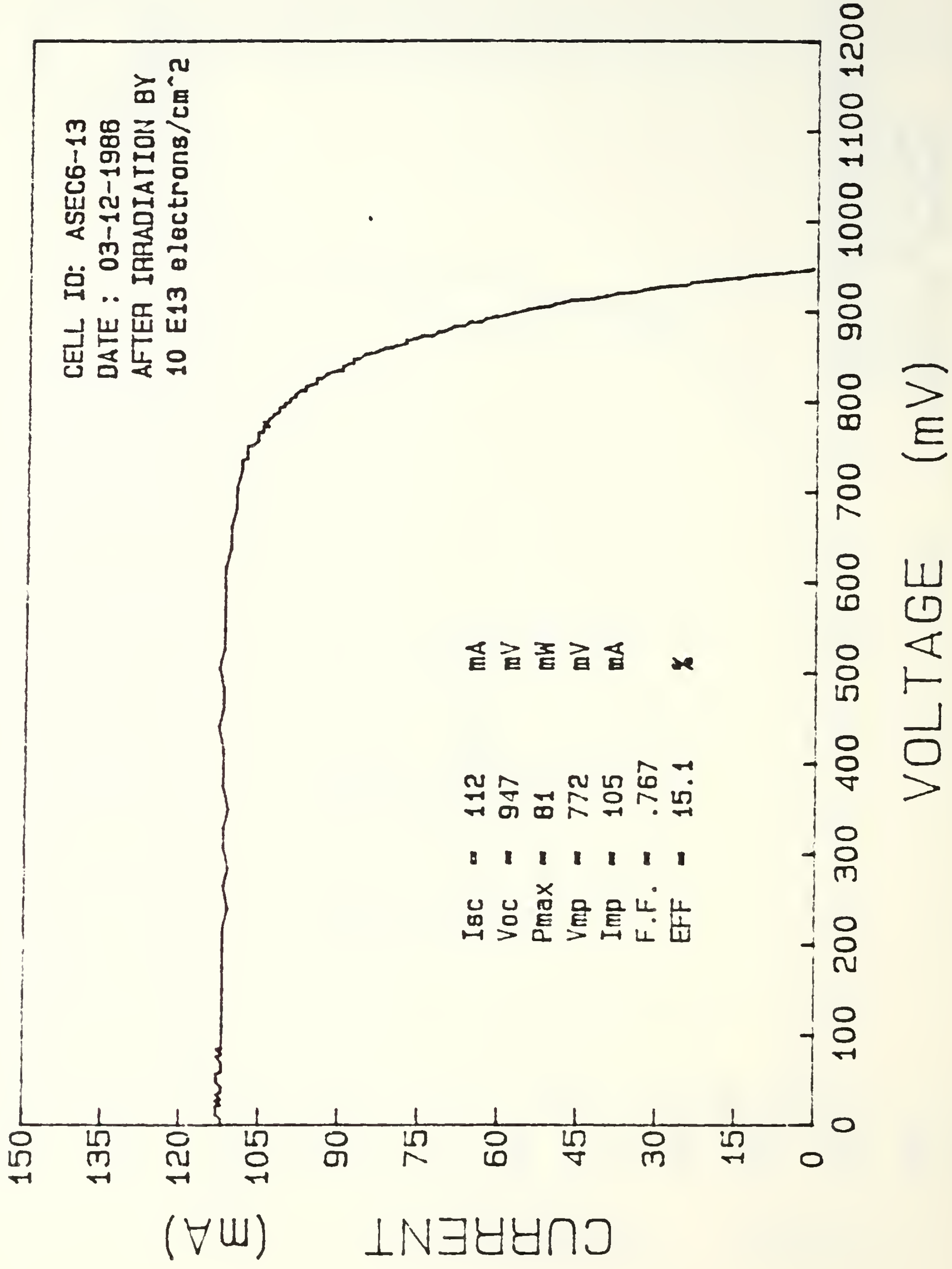


Figure 45. Post-Irradiation I-V Curve for ASEC Cell Number 6 After Irradiation by 10^{13} e/cm^2.

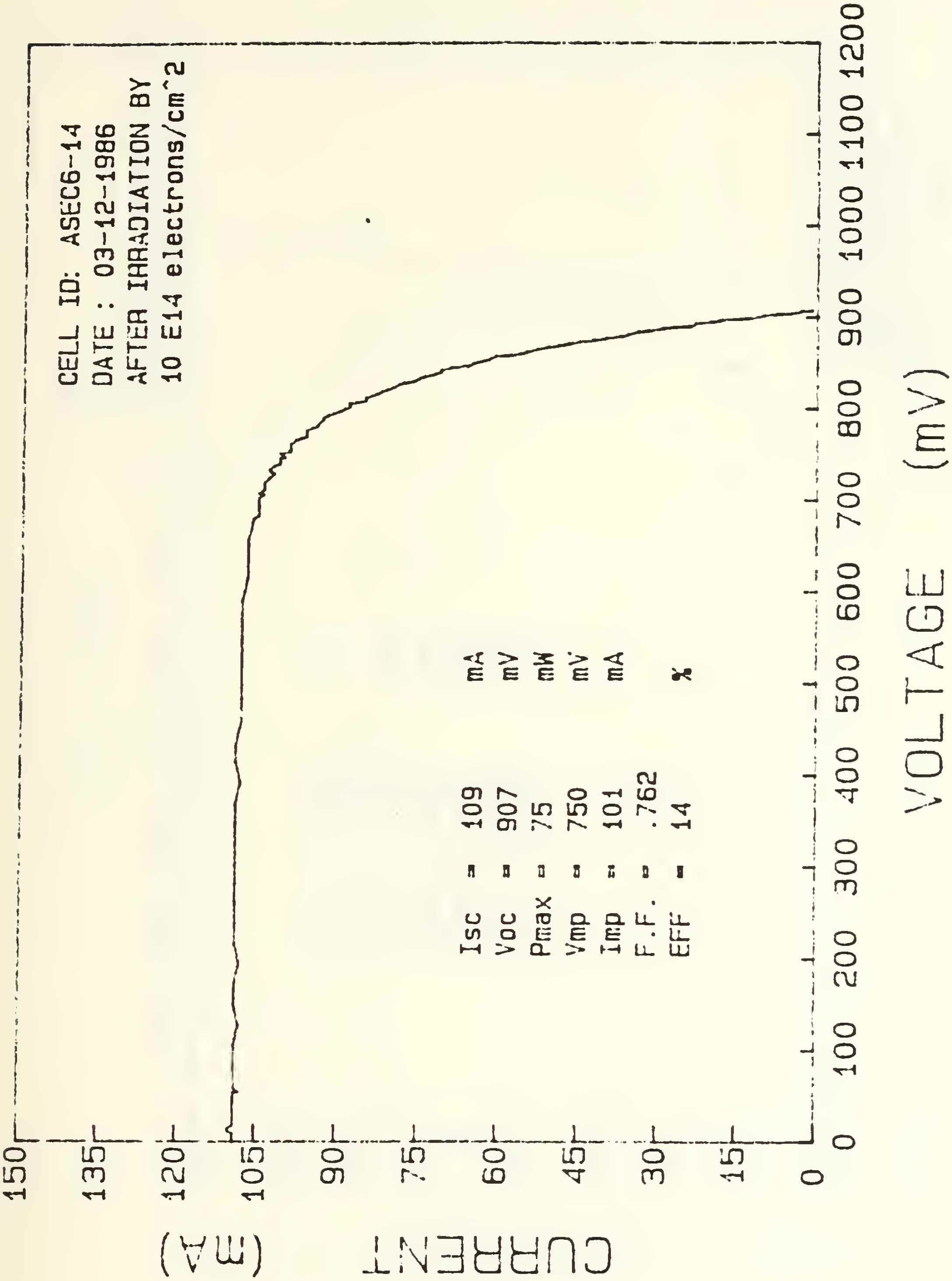


Figure 46. Post-Irradiation I-V Curve for ASEC Cell Number 6 After Irradiation by 10^{14} e/cm^2.

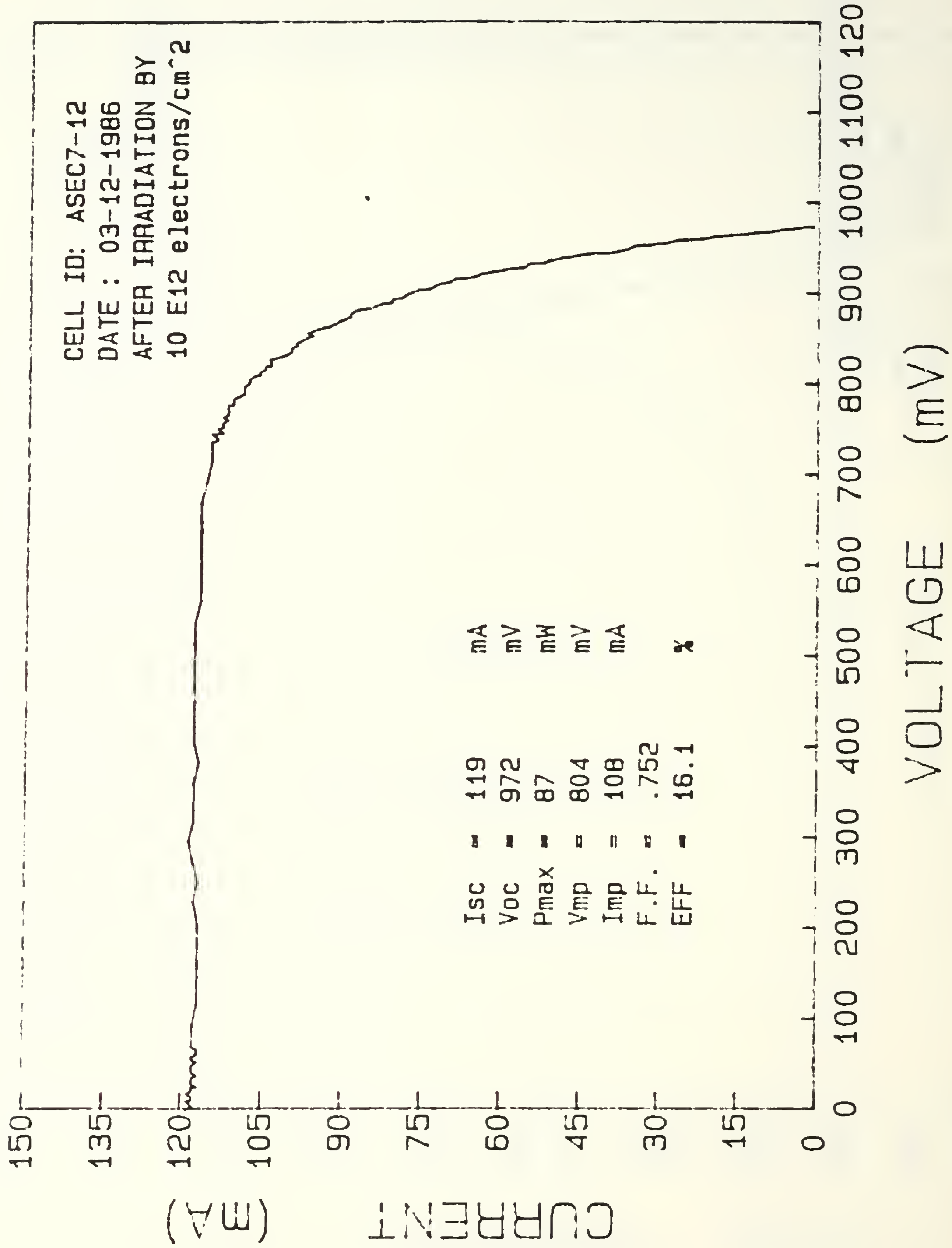


Figure 47. Post-Irradiation I-V Curve for ASEC Cell Number 7 After Irradiation by 10^{12} e/cm^2.

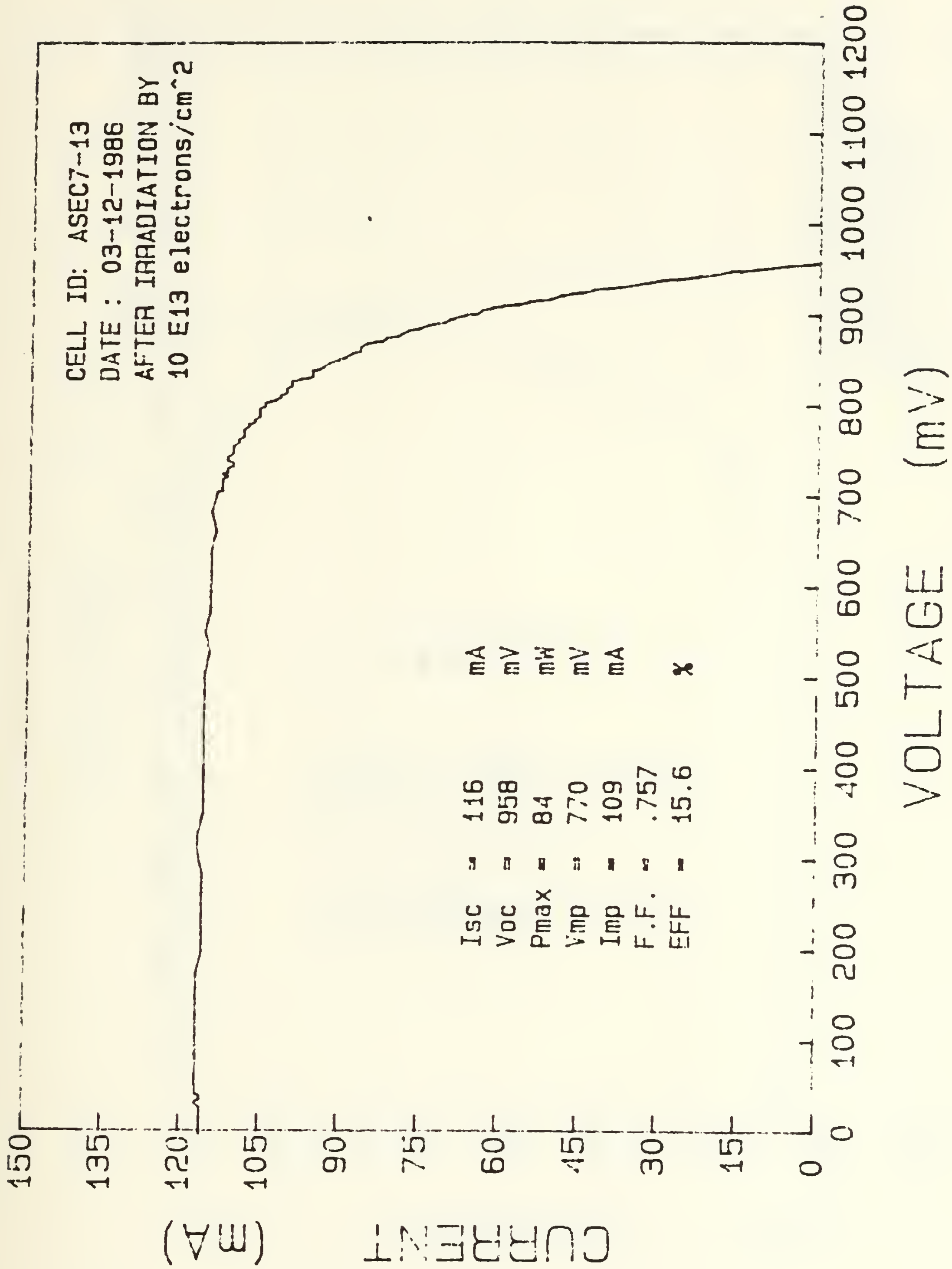


Figure 48. Post-Irradiation I-V Curve for ASEC Cell Number 7 After Irradiation by 1013 e/cm2.

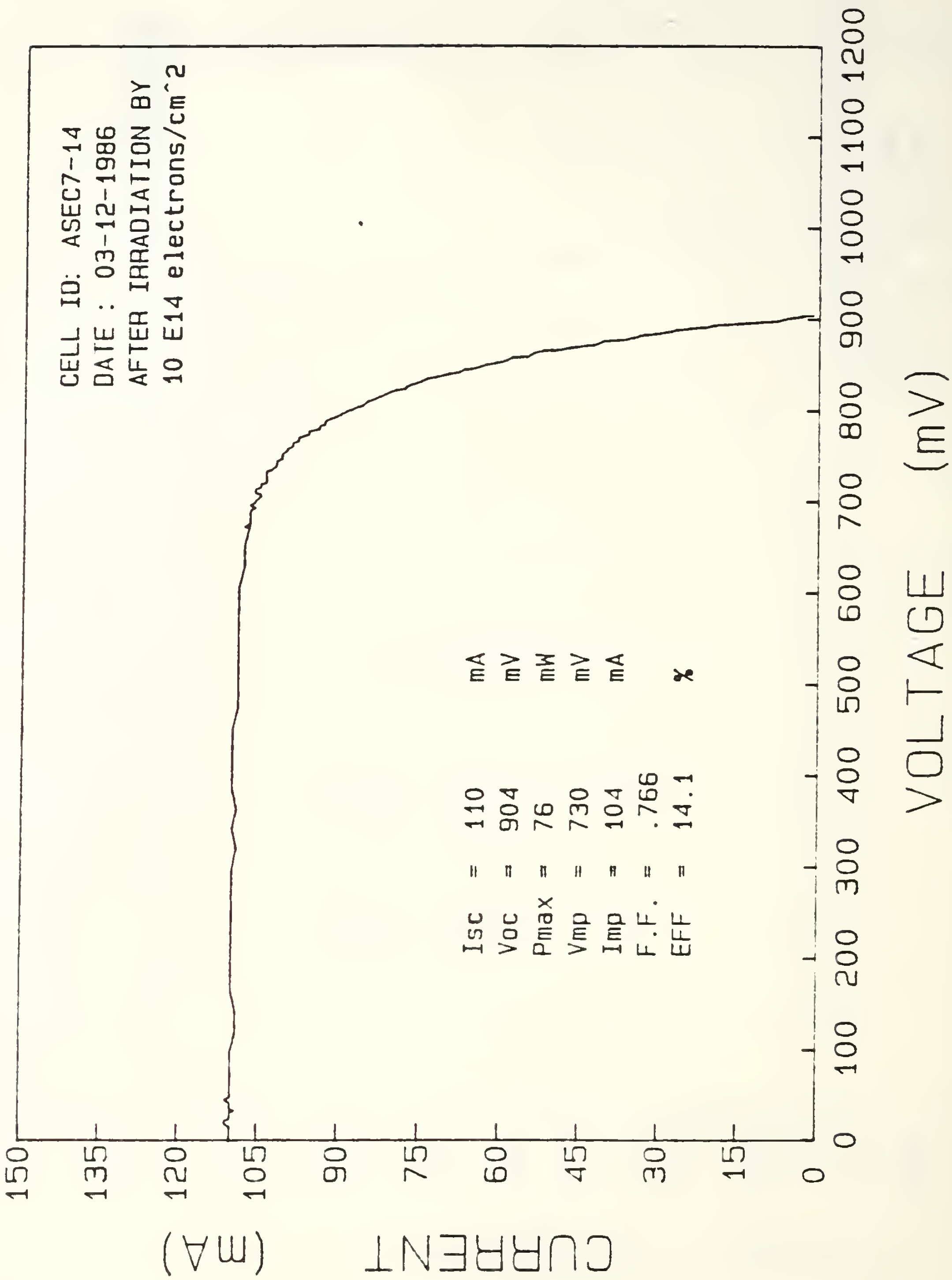


Figure 49. Post-Irradiation I-V Curve for ASEC Cell Number 7 After Irradiation by 1014 e/cm2.

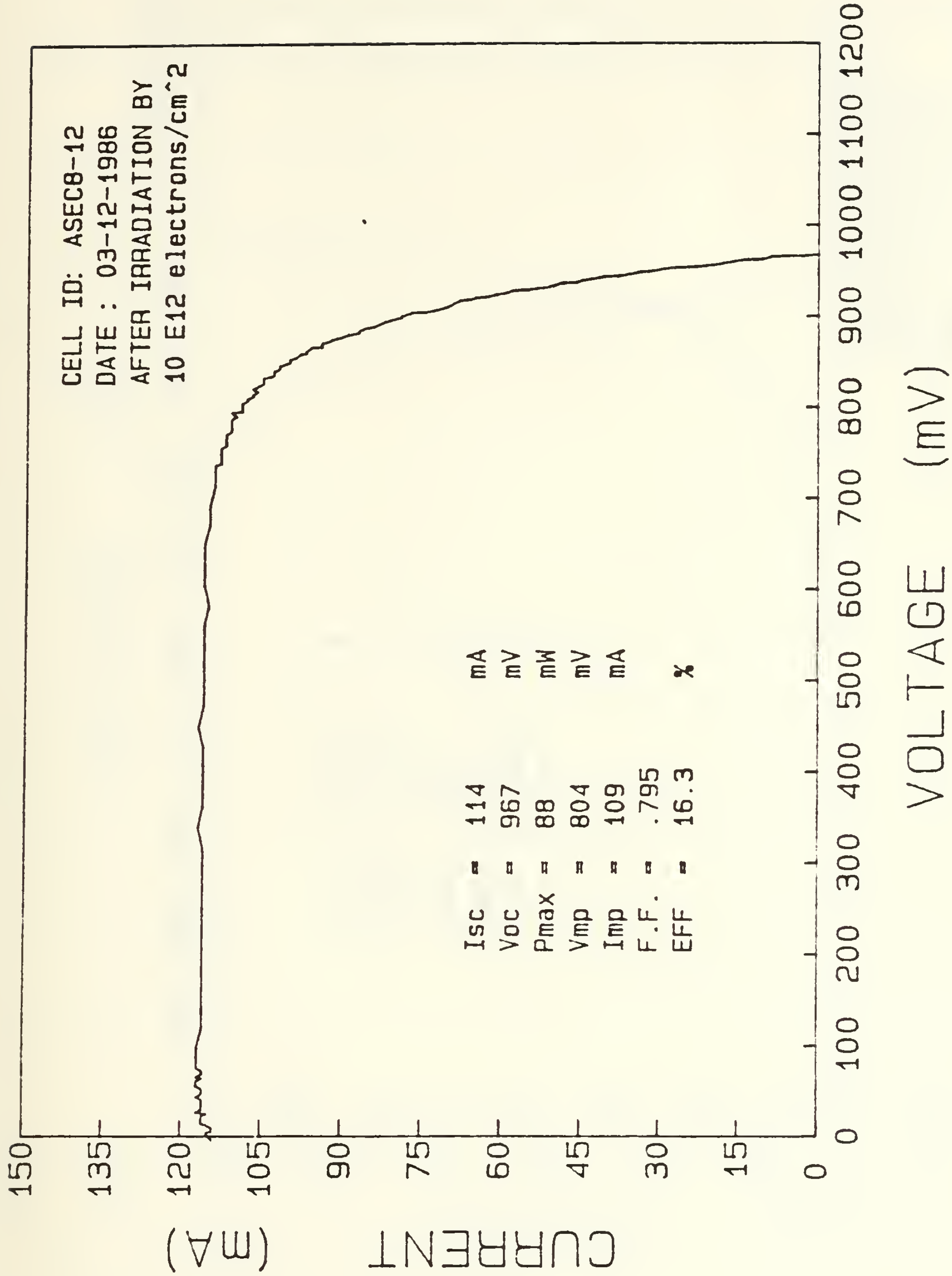


Figure 50. Post-Irradiation I-V Curve for ASEC Cell Number 8 After Irradiation by 10^{12} e/cm^2.

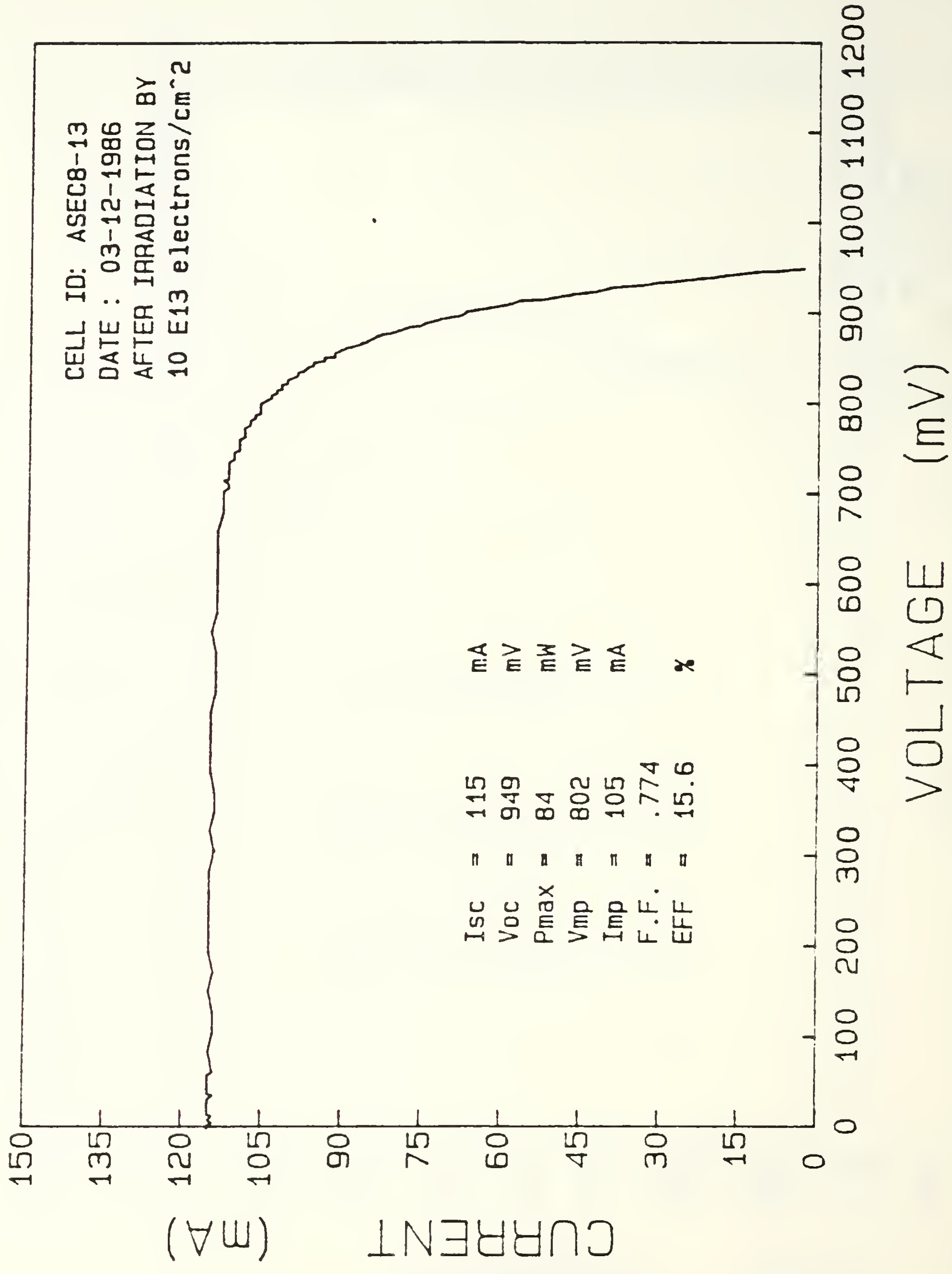


Figure 51. Post-Irradiation I-V Curve for ASEC Cell Number 8 After Irradiation by 10^{13} e/cm^2.

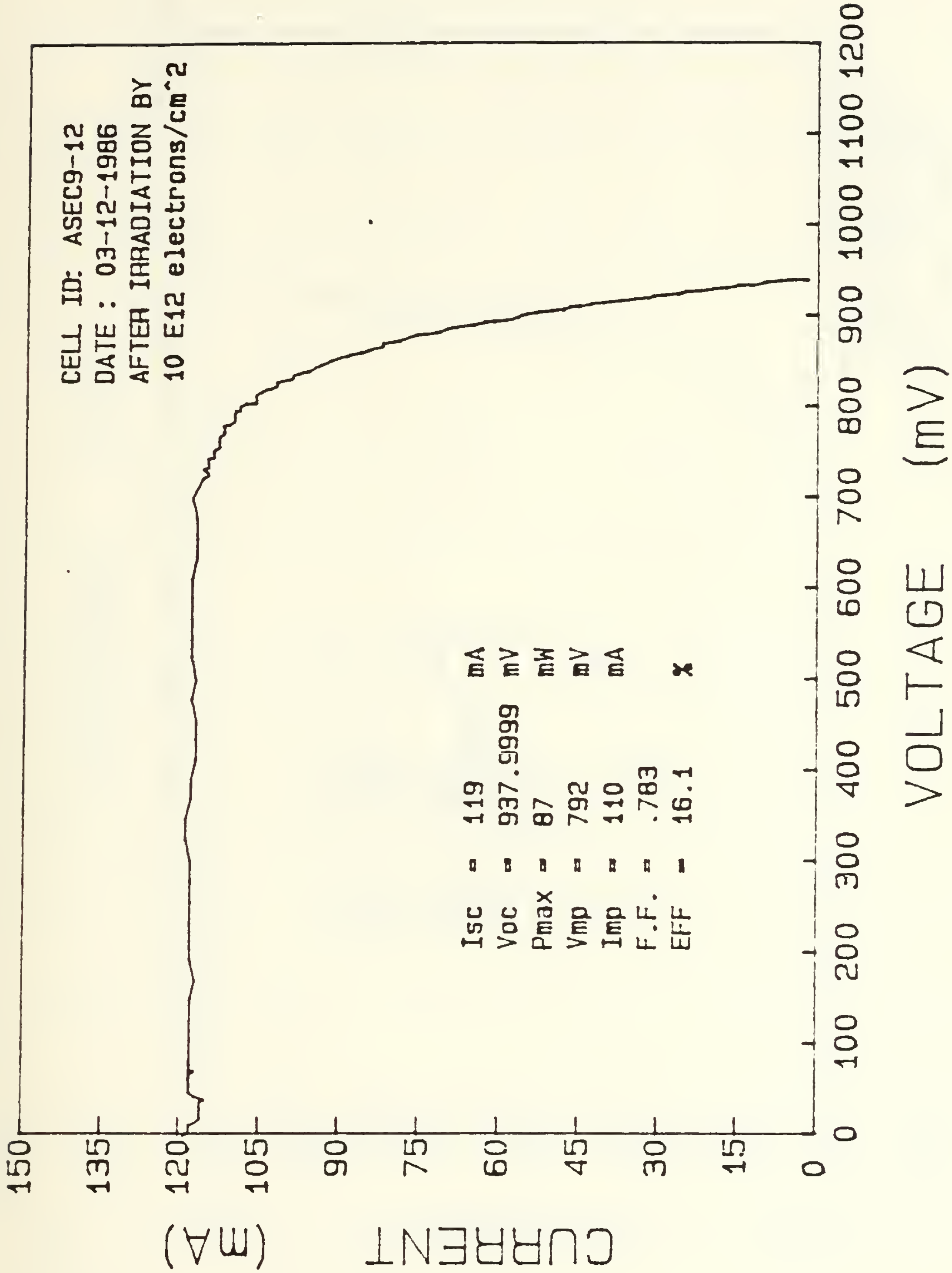


Figure 52. Post-Irradiation I-V Curve for ASEC Cell Number 9 After Irradiation by 10^{12} e/cm^2.

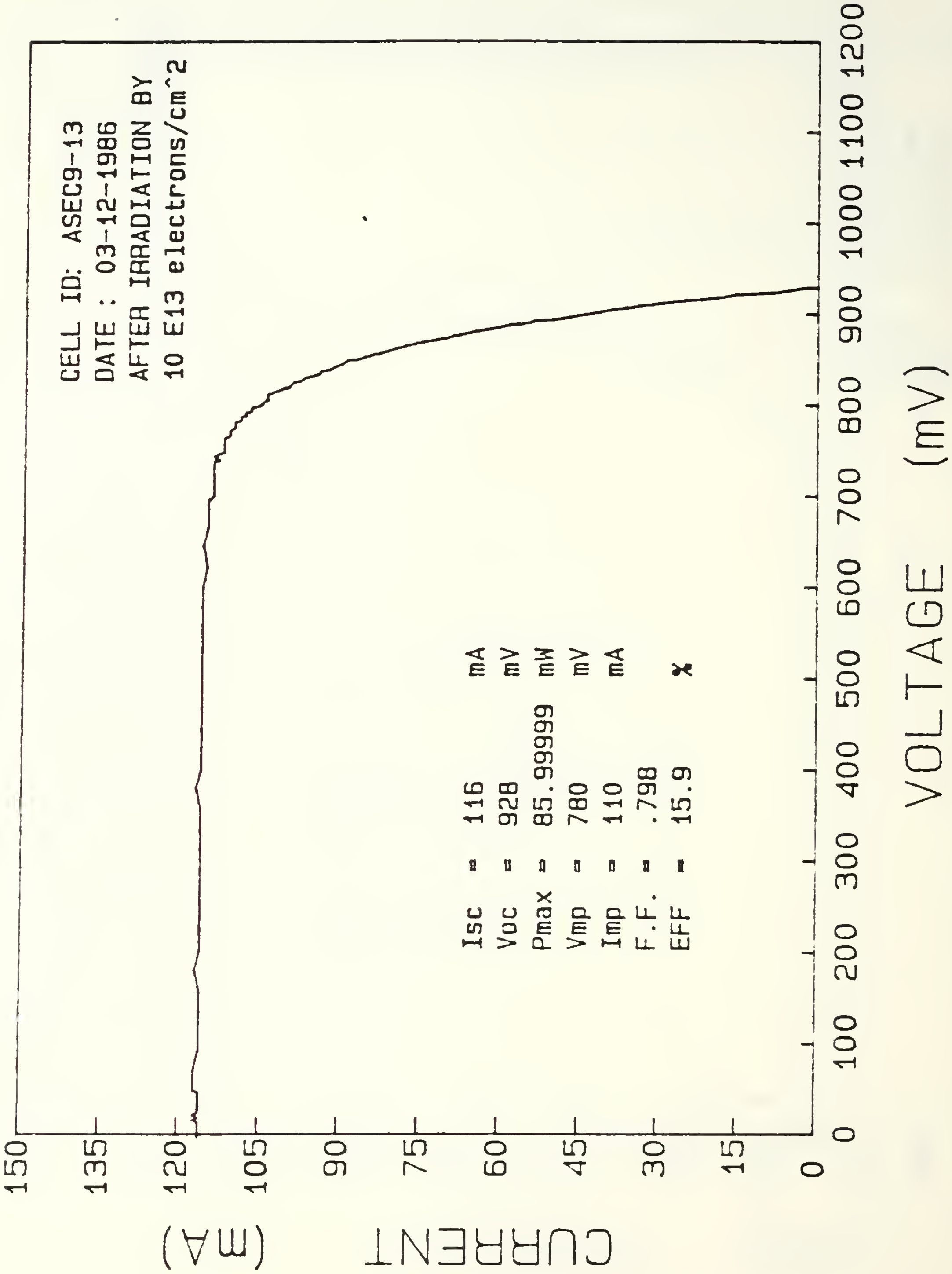


Figure 53. Post-Irradiation I-V Curve for ASEC Cell Number 9 After Irradiation by 10^{13} e/cm^2.

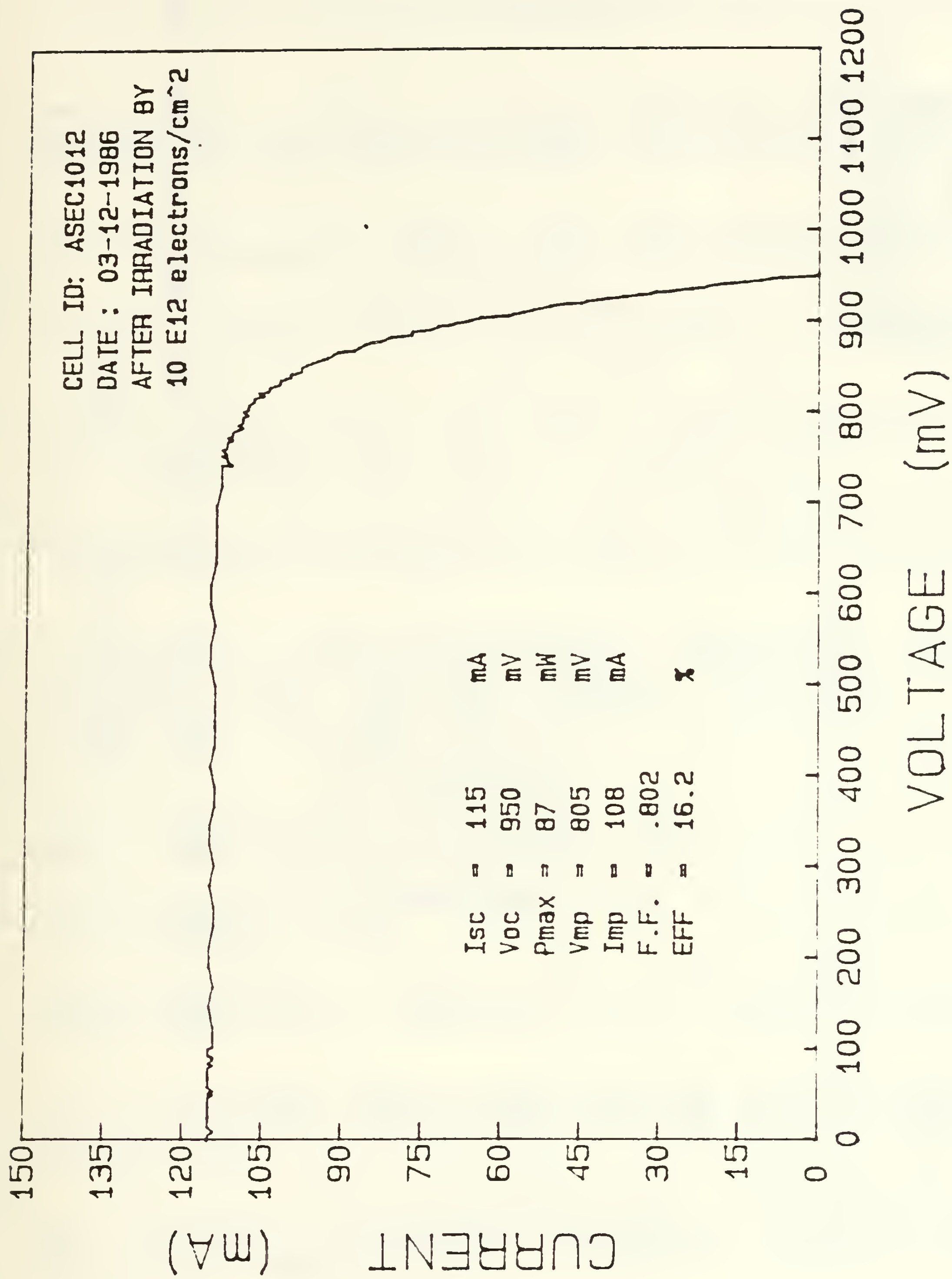


Figure 54. Post-Irradiation I-V Curve for ASEC Cell Number 10 After Irradiation by 10^{12} e/cm^2.

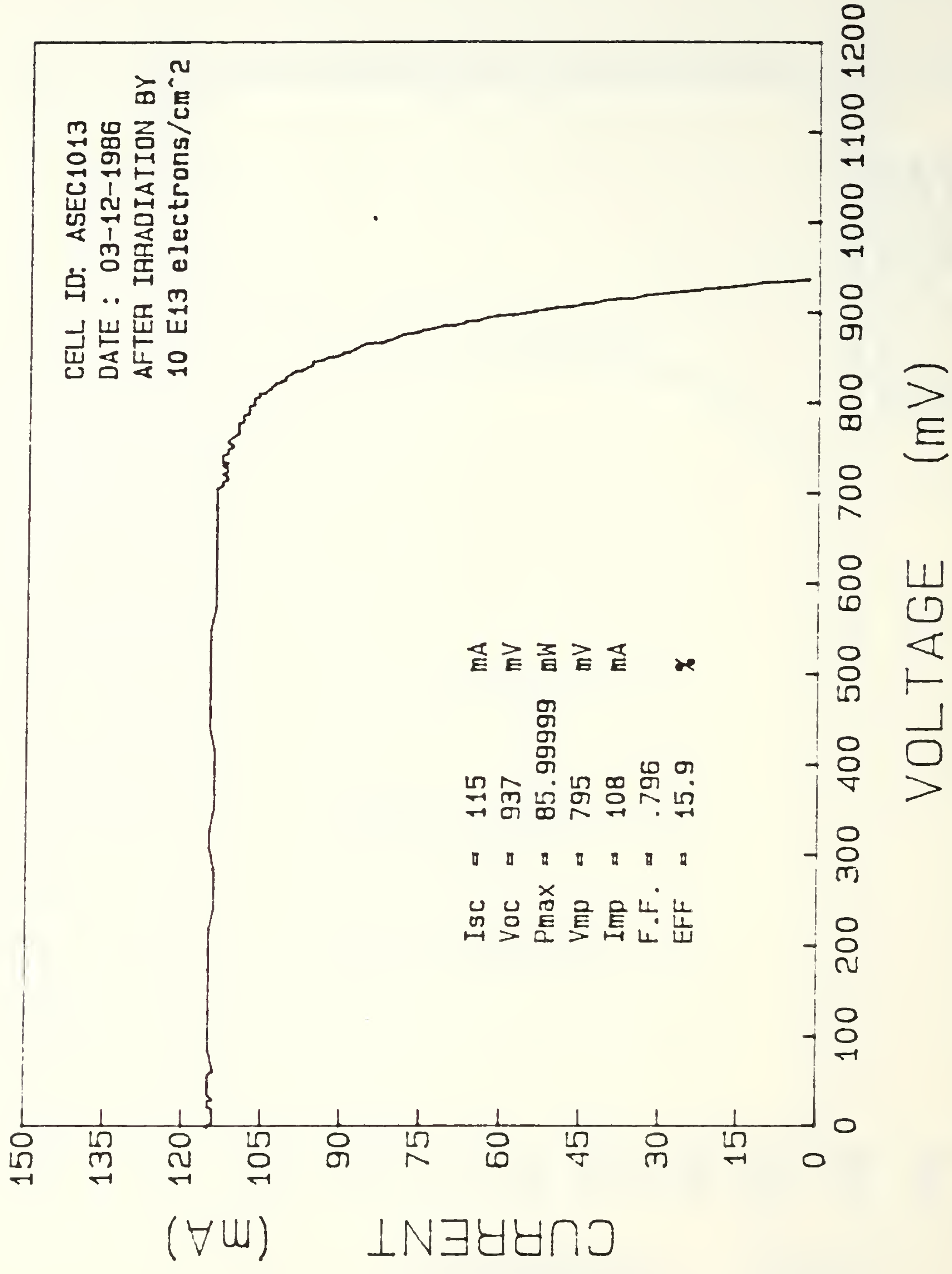


Figure 55. Post-Irradiation I-V Curve for ASEC Cell Number 10 After Irradiation by 10^{13} e/cm2.

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